Off-shell Higgs signal and total width determination at the LHC

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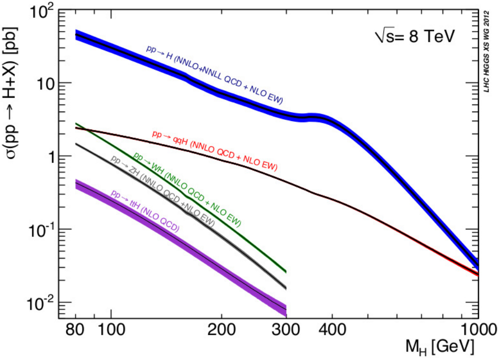
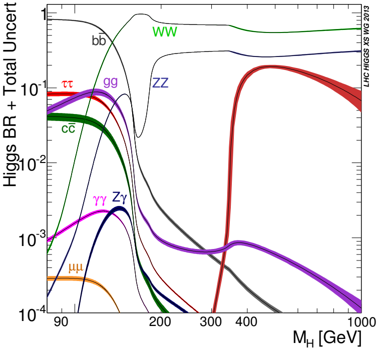
Outline

- Introduction
- Sizeable off-shell Higgs production for $H \to ZZ$ and $H \to WW$
- Implications for Higgs width constraints
- MCFM, CMS and ATLAS results
- Higgs width via interferometry in $H \to \gamma\gamma$
- Model builder's considerations, BSM searches
- Summary

SM Higgs boson production and decay at the LHC





Discovery publications:

ATLAS, *Observation of a new particle in the search for the SM Higgs boson ...*, Phys. Lett. B **716** (2012) 1.

CMS, *Observation of a new boson at a mass of 125 GeV ...*, Phys. Lett. B **716** (2012) 30.

And many papers with updates and more detailed characterisation (couplings, spin/CP), e.g.:

ATLAS, *Measurements of Higgs boson production and couplings in diboson final states ...*, Phys. Lett. B **726** (2013) 88; ATLAS, *Updated coupling measurements of the Higgs boson ...*, ATLAS-CONF-2014-009; ATLAS, *Evidence for the spin-0 nature of the Higgs boson ...*, Phys. Lett. B **726** (2013) 120.

CMS, *Observation of a new boson with mass near 125 GeV ...*, JHEP **1306** (2013) 081; CMS, *Study of the mass and spin-parity of the Higgs boson candidate via its decays to Z boson pairs*, Phys. Rev. Lett. **110** (2013) 081803; CMS, *Measurement of the properties of a Higgs boson in the four-lepton final state*, Phys. Rev. D **89** (2014) 092007.

SM Higgs boson production and decay at the LHC

Experimental studies have been informed by numerous theoretical papers (too many to list), summarised in Higgs physics reviews, e.g.:

A. Djouadi, *The Anatomy of electro-weak symmetry breaking. I: The Higgs boson in the standard model*, Phys. Rept. **457** (2008) 1.

A. Djouadi, *The Anatomy of electro-weak symmetry breaking. II. The Higgs bosons in the minimal supersymmetric model*, Phys. Rept. **459** (2008) 1.

A. Djouadi, *Higgs Physics: Theory*, Pramana **79** (2012) 513.

D. Carmi, A. Falkowski, E. Kuflik, T. Volansky and J. Zupan, *Higgs After the Discovery: A Status Report*, JHEP **1210** (2012) 196.

L. Reina, *TASI 2011: lectures on Higgs-Boson Physics*, arXiv:1208.5504 [hep-ph].

S. Dittmaier and M. Schumacher, *The Higgs Boson in the Standard Model - From LEP to LHC: Expectations, Searches, and Discovery of a Candidate*, Prog. Part. Nucl. Phys. **70** (2013) 1.

Higgs Working Group Report of the Snowmass 2013 Community Planning Study, arXiv:1310.8361 [hep-ex].

J. Ellis, *Higgs Physics*, arXiv:1312.5672 [hep-ph].

H. E. Logan, *TASI 2013 lectures on Higgs physics within and beyond the Standard Model*, arXiv:1406.1786 [hep-ph].

and the LHC Higgs Cross Section Working Group reports (also other WGs, see above):

LHC Higgs Cross Section WG, *Handbook of LHC Higgs Cross Sections: 1. Inclusive Observables*, CERN-2011-002.

LHC Higgs Cross Section WG, *Handbook of LHC Higgs Cross Sections: 2. Differential Distributions*, CERN-2012-002.

LHC Higgs Cross Section WG, *Handbook of LHC Higgs Cross Sections: 3. Higgs Properties*, CERN-2013-004.

LHC Higgs Cross Section WG, Interim recommendations to explore the coupling structure of a Higgs-like particle, arXiv:1209.0040 [hep-ph].

bottom line: no compelling Standard Model deviations found so far, search continues

Higgs width measurement in a nutshell

- Total Higgs width Γ_H is not a fundamental parameter of the theory, but of great phenomenological interest (Higgs mechanism $\rightarrow$ overall coupling strength)
- Direct Higgs width measurement via resonance shape is limited at LHC by experimental mass resolution of $\mathcal{O}(1)$ GeV (CMS: $\Gamma_H < 3$ GeV in $H \rightarrow \gamma\gamma$, but note that $\Gamma_{H,SM} \approx 4$ MeV)
- All resonant Higgs cross sections depend on Γ_H, therefore Γ_H and couplings cannot be determined at the LHC (on-peak) without theoretical assumptions M. Duhrssen et al. (2004), LHC Higgs Cross Section WG (2012)
- For broad class of models, assuming upper limit for HWW or HZZ coupling (e.g. SM) $\rightarrow$ upper bound for Γ_H $(\Gamma_H = \mathcal{O}(\Gamma_{H,SM}))$ M. Peskin (2012); B. Dobrescu, J. Lykken (2013)
- Assuming no BSM Higgs decays, and Higgs coupling parameterisations, can fit Higgs width to data and agreement with SM Higgs width is found J. Ellis, You (2013)
- $e^+e^- \rightarrow Z(H \rightarrow$ all): construct recoil mass and measure HZZ coupling $\rightarrow \Gamma_H$ can be determined indirectly, ILC: 6%–11% accuracy T. Han et al. (2013), M. Peskin (2013)
- Direct threshold scan at muon collider: Γ_H accuracy 4%–9% T. Han, Z. Liu (2013)
- Model-independent Γ_H determination (at LHC?) could confirm SM or could provide evidence for BSM Higgs interactions

Sizeable off-shell Higgs production for $H \to VV$

Narrow-width approximation (NWA): $D(q^2) = \frac{1}{(q^2 - M^2)^2 + \Gamma^2 M^2} \sim \frac{\pi}{M\,\Gamma}\,\delta\left(q^2 - M^2\right)$

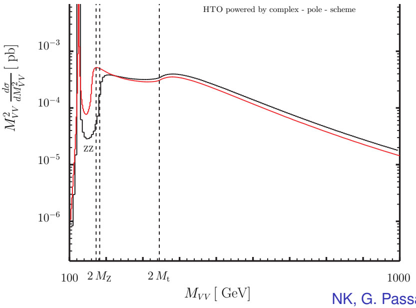
$$\sigma = \frac{1}{2s}\left[\int_{q^2_{\text{min}}}^{q^2_{\text{max}}} \frac{dq^2}{2\pi}\left(\int d\phi_p |\mathcal{M}_p(q^2)|^2 D(q^2) \int d\phi_d |\mathcal{M}_d(q^2)|^2\right)\right]$$

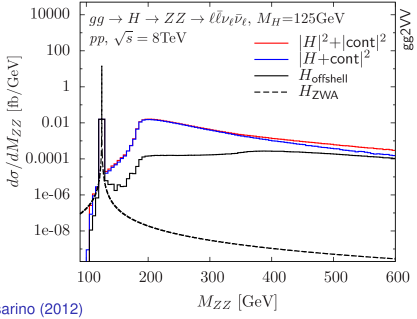
SM: $\frac{\Gamma_H}{M_H} < 10^{-4}$

$$\sigma_{\text{NWA}} = \frac{1}{2s}\left(\int d\phi_p |\mathcal{M}_p(M^2)|^2\right)\left(\int_{-\infty}^{\infty} \frac{dq^2}{2\pi} D(q^2)\right)\left(\int d\phi_d |\mathcal{M}_d(M^2)|^2\right)$$

for $H \to f\bar{f}$: $|\mathcal{M}_d(q^2)|^2 \sim m_f^2 q^2$, for $H \to VV$: $|\mathcal{M}_d(q^2)|^2 \sim (q^2)^2$ for $\sqrt{q^2} \gtrsim 2\,M_V$

Enhanced off-shell Higgs signal contribution of $\mathcal{O}(10\%)$ in ggF & VBF $\to$ NWA jeopardized:





NK, G. Passarino (2012)

Approach: initially: suppress with cuts, more recently: take into account and exploit

Higgs width determination and off-resonance signal

indirect Higgs width determination via on- and off-peak Higgs cross section

F. Caola, K. Melnikov (2013); also: S. Martin (2012); L. Dixon, Y. Li (2013) (see $H \to \gamma\gamma$ below)

$$|\mathcal{M}_{i\to H\to f}|^2 = \frac{|\mathcal{M}_i|^2\,|\mathcal{M}_f|^2}{|p_H^2 - M_H^2 + iM_H\Gamma_H|^2}$$

resonance contribution to signal cross section ("on-peak"): $\sigma_{i\to H\to f} \overset{\text{NWA}}{\propto} \frac{g_i^2 g_f^2}{\Gamma_H}$

NWA scaling degeneracy: σ unchanged if $g_i \to \xi\, g_i,\;\; g_f \to \xi\, g_f,\;\; \Gamma_H \to \xi^4\, \Gamma_H$

$$\sqrt{p_H^2} - M_H \gg \mathcal{O}(\Gamma_H) \;\;\to\;\; p_H^2 - M_H^2 \gg M_H\Gamma_H \;\;\to\;\; |\mathcal{M}_{i\to H\to f}|^2 \approx \frac{|\mathcal{M}_i|^2\,|\mathcal{M}_f|^2}{|p_H^2 - M_H^2|^2}$$

off-resonance contribution ("off-peak"): $\sigma_{i\to H\to f}\left(\sqrt{p_H^2} - M_H \gg \mathcal{O}(\Gamma_H)\right) \propto g_i^2 g_f^2$

sizeable off-resonance contribution to signal cross section is independent of Higgs width, and therefore "breaks" NWA scaling degeneracy: $\sigma_{\text{off-peak}}/\sigma_{\text{on-peak}} \propto \Gamma_H$

claim: competitive constraints on Higgs width without assumptions feasible with LHC data

large interference with cont. background (necessary to prevent unitarity violation) weakens bounds

MCFM analysis

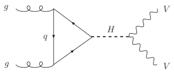
J. Campbell, K. Ellis, C. Williams (2013) (update of Caola-Melnikov analysis)

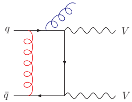
CMS Higgs selection cuts are applied:

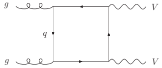
$p_{T\ell 1} > 20$ GeV, $p_{T\ell 2} > 10$ GeV, $p_{Te} > 7$ GeV, $p_{T\mu} > 5$ GeV, $|\eta_\mu| < 2.4$, $|\eta_e| < 2.5$, $M_{\ell\bar{\ell}} > 4$ GeV, $M_{4\ell} > 100$ GeV, 40 GeV $< M_{\ell\bar{\ell},\text{closest}} < 120$ GeV, 12 GeV $< M_{\ell\bar{\ell},\text{other}} < 120$ GeV (relative to M_Z)

Best prediction cross sections for $pp \to H \to ZZ \to e^-e^+\mu^-\mu^+$ in fb, obtained using the running scale $m_{4\ell}/2$:

			$m_{4\ell} > 130$ GeV		$m_{4\ell} > 300$ GeV	
Energy	PDF	σ^H_{peak}	σ^H_{off}	σ^I_{off}	σ^H_{off}	σ^I_{off}
7 TeV	MSTW	0.203	0.025	-0.053	0.017	-0.025
	CTEQ	0.192	0.021	-0.047	0.015	-0.021
8 TeV	MSTW	0.255	0.034	-0.073	0.025	-0.036
	CTEQ	0.243	0.031	-0.065	0.022	-0.031
13 TeV	MSTW	0.554	0.108	-0.215	0.085	-0.122
	CTEQ	0.530	0.100	-0.199	0.077	-0.111







MCFM analysis

For $\sigma_{off} = \sigma^H_{off} + \sigma^I_{off}$ with $\sqrt{s} = 8$ TeV and MSTW PDF set:

$$\sigma_{off}(m_{4\ell} > 130\text{ GeV}) = \underbrace{0.034\left(\frac{\Gamma_H}{\Gamma_H^{SM}}\right)}_{\text{Higgs signal}} \underbrace{-0.073\sqrt{\frac{\Gamma_H}{\Gamma_H^{SM}}}}_{\text{interference}}$$

$$\sigma_{off}(m_{4\ell} > 300\text{ GeV}) = 0.025\left(\frac{\Gamma_H}{\Gamma_H^{SM}}\right) - 0.036\sqrt{\frac{\Gamma_H}{\Gamma_H^{SM}}}$$

Normalising to the number of events observed at the peak one can estimate number of Higgs-related off-peak events (properly combining 7 and 8 TeV data used in CMS $H \to ZZ \to 4\ell$ analysis):

$$N^{4\ell}_{off}(m_{4\ell} > 130\text{ GeV}) = 2.78\left(\frac{\Gamma_H}{\Gamma_H^{SM}}\right) - 5.95\sqrt{\frac{\Gamma_H}{\Gamma_H^{SM}}}$$

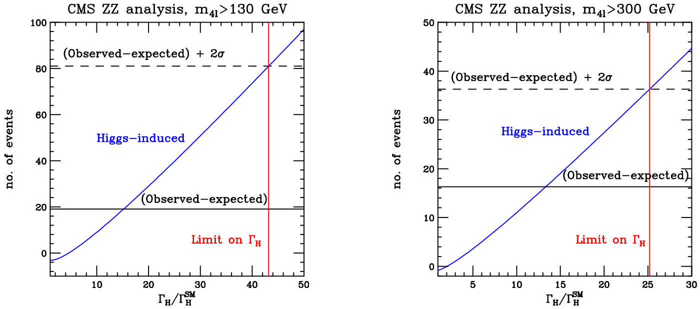
$$N^{4\ell}_{off}(m_{4\ell} > 300\text{ GeV}) = 2.02\left(\frac{\Gamma_H}{\Gamma_H^{SM}}\right) - 2.91\sqrt{\frac{\Gamma_H}{\Gamma_H^{SM}}}$$

Second term accounts for interference between $gg \to H \to ZZ \to 4\ell$ (Higgs signal amplitude) and $gg \to ZZ \to 4\ell$ (continuum background amplitude)

MCFM analysis

Higgs width bounds from cut-based analysis

Using event number observed in off-peak region (451) and number expected from continuum background only (431 ± 31):



$\Gamma_H < 43.2\,\Gamma_H^{SM}$ (95% CL), $(m_{4\ell} > 130 \text{ GeV analysis})$

$\Gamma_H < 25.2\,\Gamma_H^{SM}$ (95% CL), $(m_{4\ell} > 300 \text{ GeV analysis})$

Method can be applied to $H \to WW$ channel (M_T), comparable bounds appear feasible MCFM (2013)

MCFM analysis

Higgs width bounds from matrix element method ($H \to ZZ$)

Matrix element method: optimize discrimination using fully differential information

Associate probabilistic weight with each event:

$$P(\phi) = \frac{1}{\sigma} \sum_{i,j} \int dx_1 dx_2 \, \delta(x_1 x_2 s - Q^2) f_i(x_1) f_j(x_2) \hat{\sigma}_{ij}(x_1, x_2, \phi)$$

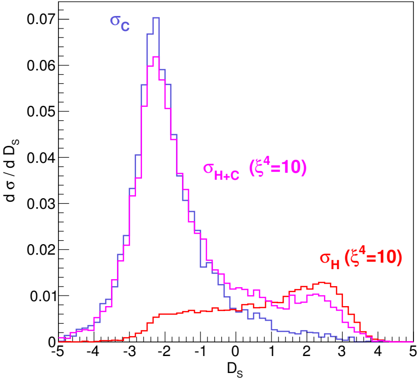
$P_{q\bar{q}}$: $q\bar{q}$ induced continuum background

P_{gg} : gg induced contributions (incl. Higgs signal, cont. bkg. & interf.)

P_H : gg induced Higgs amplitude squared

Discriminant:

$$D_S = \log\left(\frac{P_H}{P_{gg} + P_{q\bar{q}}}\right)$$



$\Gamma_H < \left(15.7^{-2.9}_{+3.9}\right) \Gamma_H^{SM}$ (95% CL), $(D_S > 1)$

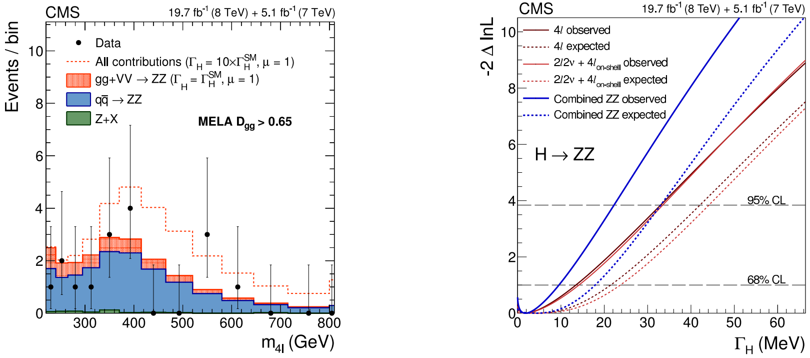
bound $1.6\times$ better than for $m_{4\ell} > 300$ GeV

CMS analysis

CMS-HIG-14-002 (May 2014)

improvements:

- include $2\ell 2\nu$ final states
- include VBF channel (contributes $\sim 7\%$ on peak, and $\mathcal{O}(10\%)$ above $2M_Z$)
- include known QCD and EW corrections F. Caola, T. Kasprzik, G. Passarino, M. Zaro et al.
- slightly different kinematic discriminant ($P_H \to P_{gg}$), backgrounds fully considered



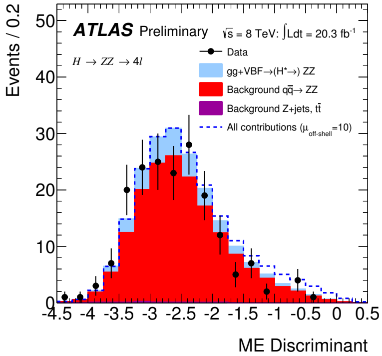
$$\Gamma_H < 5.4\,\Gamma_H^{SM} \quad \text{(95\% CL)}$$

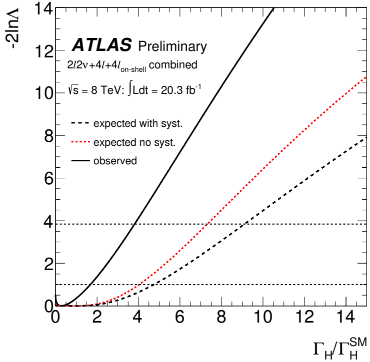
ATLAS analysis

ATLAS-CONF-2014-042 (July 2014)

improvements:

- similar to CMS, thorough consideration of systematic uncertainties
- provide results as function of the unknown $gg \to ZZ$ background K-factor, variation: $[0.5, 2] \times$ signal K-factor
- off-shell signal strength in $[5.6, 9.0]$ ($[6.6, 10.7]$ expected)



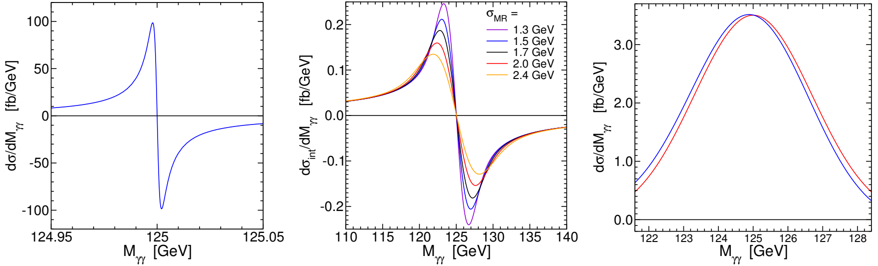


$$\Gamma_H < [4.8, 7.7]\, \Gamma_H^{SM} \quad \text{(95\% CL)}$$

Higgs width via interferometry in $H \to \gamma\gamma$

S. Martin (2012) (proposal and LO analysis)

Higgs signal continuum background interference induces sizeable peak shift in $gg \to H \to \gamma\gamma$ (but negligible in $gg \to H \to ZZ^*$)



left fig.: interference contribution (real term) before detector resolution effects

center fig.: interference contribution (real term) for different mass resolutions (Gaussian, σ_{MR})

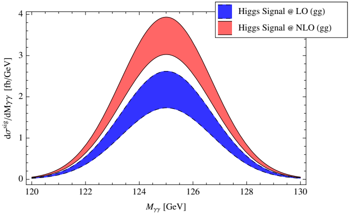
right fig.: peak shift of invariant mass distribution ($\sigma_{\text{MR}} = 1.7$ GeV): $\Delta M_{\gamma\gamma} = -120$ MeV at LO

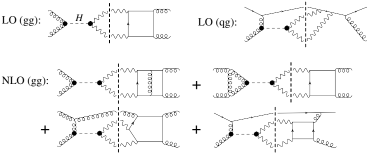
$(H \to \gamma\gamma)$+jet at LO: negligible mass peak shift (< 20 MeV for $p_{Tj} > 25$ GeV)

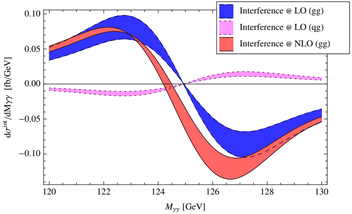
Daniel de Florian, et al. (2013); S. Martin (2013)

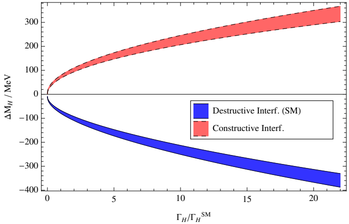
Higgs width via interferometry in $H \to \gamma\gamma$

L. Dixon, Y. Li (2013) (NLO analysis)









SM mass shift: $\Delta M_{\gamma\gamma} = -70$ MeV at NLO

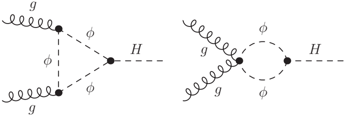
Vary Higgs width and couplings (maintaining on-peak SM signal strenghts):

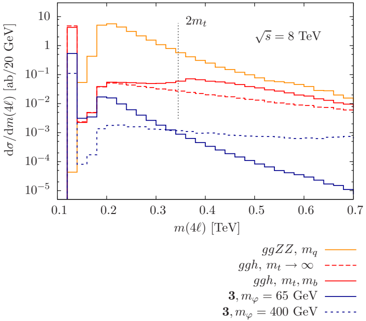
$\Gamma_H < 15\,\Gamma_H^{SM}$ (14 TeV, 3 ab^{-1}, 95% CL)

Model builder's considerations, BSM searches

Constraining higher dimensional operators with the off-shell Higgs
Limitations of model-independence
Disentangling New Physics with the off-shell Higgs boson
EFT studies including the off-shell Higgs boson

J. Gainer, J. Lykken, K. Matchev, S. Mrenna, M. Park (2014); C. Englert, M. Spannowsky (2014); M. Ghezzi, G. Passarino, S. Uccirati (2014); G. Cacciapaglia, A. Deandrea, G. Drieu La Rochelle, J. Flament (2014); A. Azatov, C. Grojean, A. Paul, E. Salvioni (2014); A. Biekoetter, A. Knochel, M. Kraemer, D. Liu, F. Riva (2014)



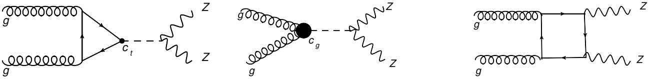


C. Englert, M. Spannowsky (2014)

EFT analysis of on- and off-shell $H \to ZZ \to 4\ell$ data

A. Azatov, C. Grojean, A. Paul, E. Salvioni (2014)

(see also G. Cacciapaglia, A. Deandrea, G. Drieu La Rochelle, J. Flament (2014))

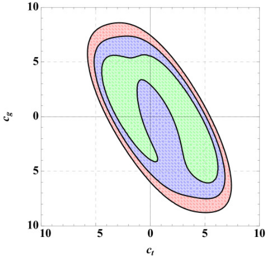


$$\mathcal{L} = -c_t \frac{m_t}{v} \bar{t}th + \frac{g_s^2}{48\pi^2} c_g \frac{h}{v} G_{\mu\nu}G^{\mu\nu}$$

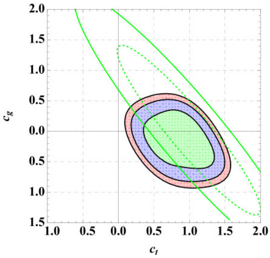
$$\mathcal{M}_{gg\to ZZ} = \mathcal{M}_h + \mathcal{M}_{bkg} = c_t\,\mathcal{M}_{c_t} + c_g\,\mathcal{M}_{c_g} + \mathcal{M}_{bkg}$$

$\sigma \sim |c_t + c_g|^2$: on-shell degeneracy $c_t + c_g = \mathrm{const}$ is broken by far-off-shell data

Constraints in (c_t, c_g) plane (68%, 95% and 99% probability contours): (not MELA improved!)



LHC 8 TeV CMS data



LHC 14 TeV $3\,\mathrm{ab}^{-1}$ data

Summary

- Direct Higgs width measurement at LHC limited by mass resolution: $\Gamma_H \lesssim 750\,\Gamma_H^{SM}$
- $M_H \approx 126$ GeV: narrow-width approx. expected to be excellent ($\Gamma_H^{\mathrm{SM}}/M_H \approx 3{\cdot}10^{-5}$)
  But: M_H dependence of Higgs decay rates $\rightarrow$
  Off-shell and interference effects are essential for $\mathcal{O}(1\%)$ accuracy
- $\mathcal{O}(5\text{–}10\%)$ off-resonance corrections to inclusive $gg \rightarrow H \rightarrow VV$ (no cuts),
  $\mathcal{O}(10\text{–}20\%)$ corrections to $gg \rightarrow H \rightarrow VV$ with acceptance/process selection cuts
- off-shell Higgs tail not Γ_H dependent $\rightarrow$ provides complementary constraints on Γ_H, couplings
- Assuming no E-dependence of relevant Higgs couplings, a bound on Γ_H can be obtained (VBF is less model-sensitive than gluon fusion)
- Optimise bound with fully differential discriminant (Matrix Element Method)
- CMS: $\Gamma_H < 5.4\,\Gamma_H^{SM}$, ATLAS: $\Gamma_H < [4.8, 7.7]\,\Gamma_H^{SM}$ (95% CL)
- $H \rightarrow \gamma\gamma$: interference-facilitated bound $\Gamma_H < 15\,\Gamma_H^{SM}$ (14 TeV, 3 ab^{-1}, 95% CL)
  fairly direct, very sensitive to detector resolution/systematic errors
- BSM searches: off-shell Higgs explored in benchmark and EFT studies at LHC and future colliders
- Can expect more surprises in Higgs physics at the LHC ...