HXSWG-WG1: Off-shell task force (Theory)

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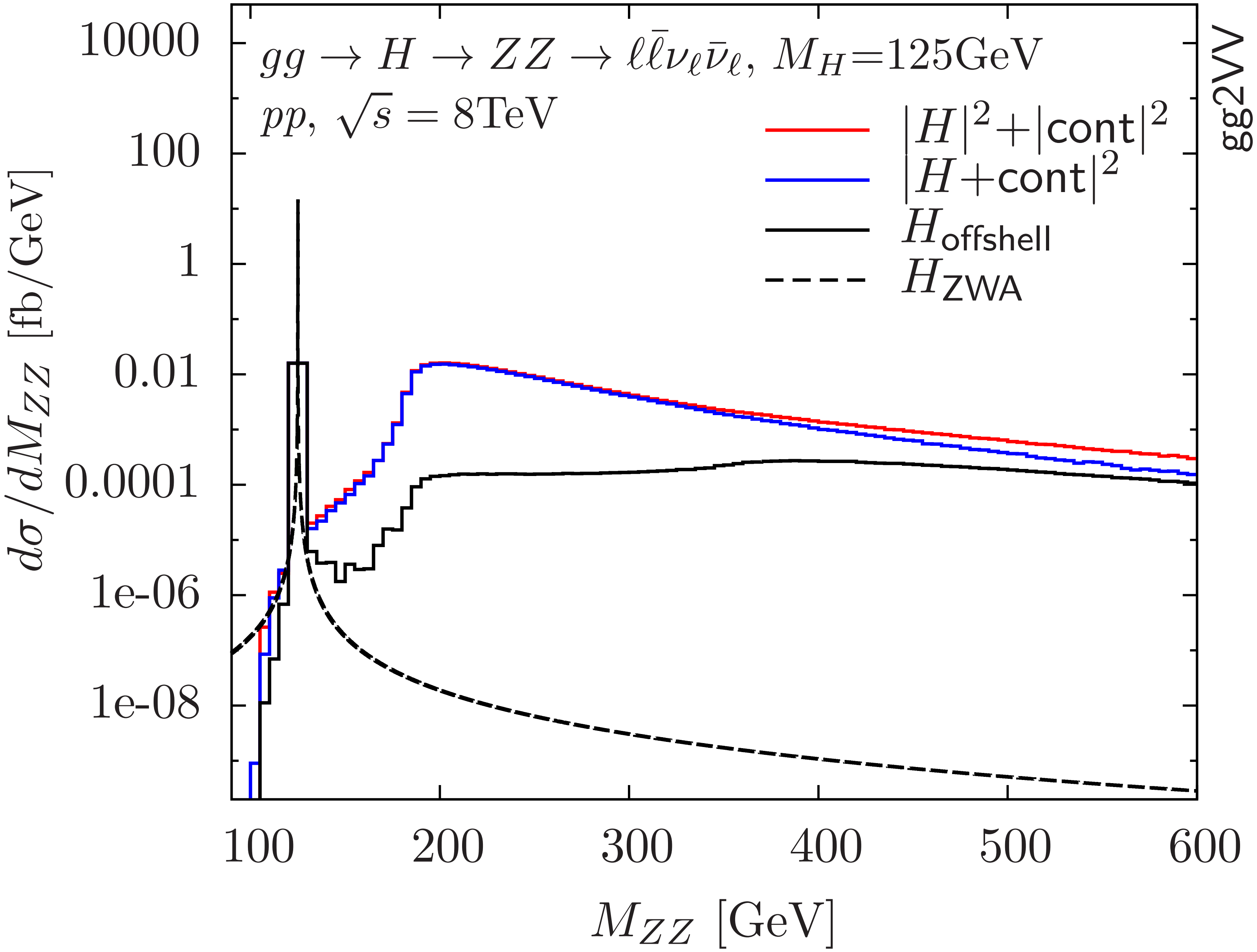
Higgs width measurement in a nutshell

- 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

H->VV: large off-shell tail of the cross-section

[Kauer, Passarino (2012)]

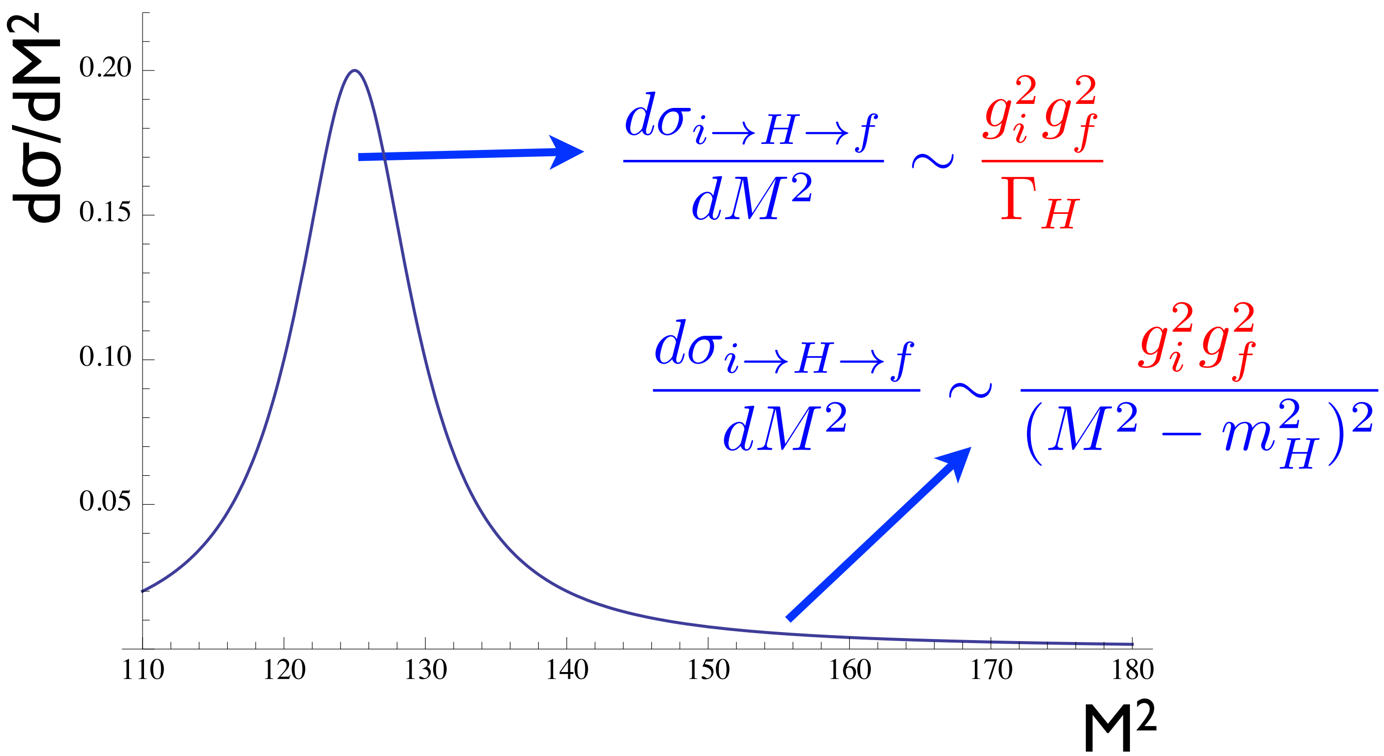


- Past the VV threshold, enhanced decay into longitudinal vector bosons compensate the rapidly falling Higgs propagator
- Small but persisting effect -> O(10%) of the peak cross-section
- Width-independent effect

- Irrelevant for traditional searches if proper selection cuts are applied
- If looked for, can give complementary information wrt traditional searches

Example: bounds on the Higgs width

[Caola, Melnikov (2013)]



- On the peak, only access to coupling x BR
- Off the peak, Γ_H independent
- Because of this, constraints on Γ_H

- Peak looks SM-like -> $\frac{g_i^2 g_f^2}{\Gamma_H} = \frac{g_{i,\mathrm{SM}}^2 g_{f,\mathrm{SM}}^2}{\Gamma_{H,\mathrm{SM}}} \longrightarrow g = \xi g_{\mathrm{SM}},\ \Gamma_H = \xi^4 \Gamma_{H,\mathrm{SM}}$

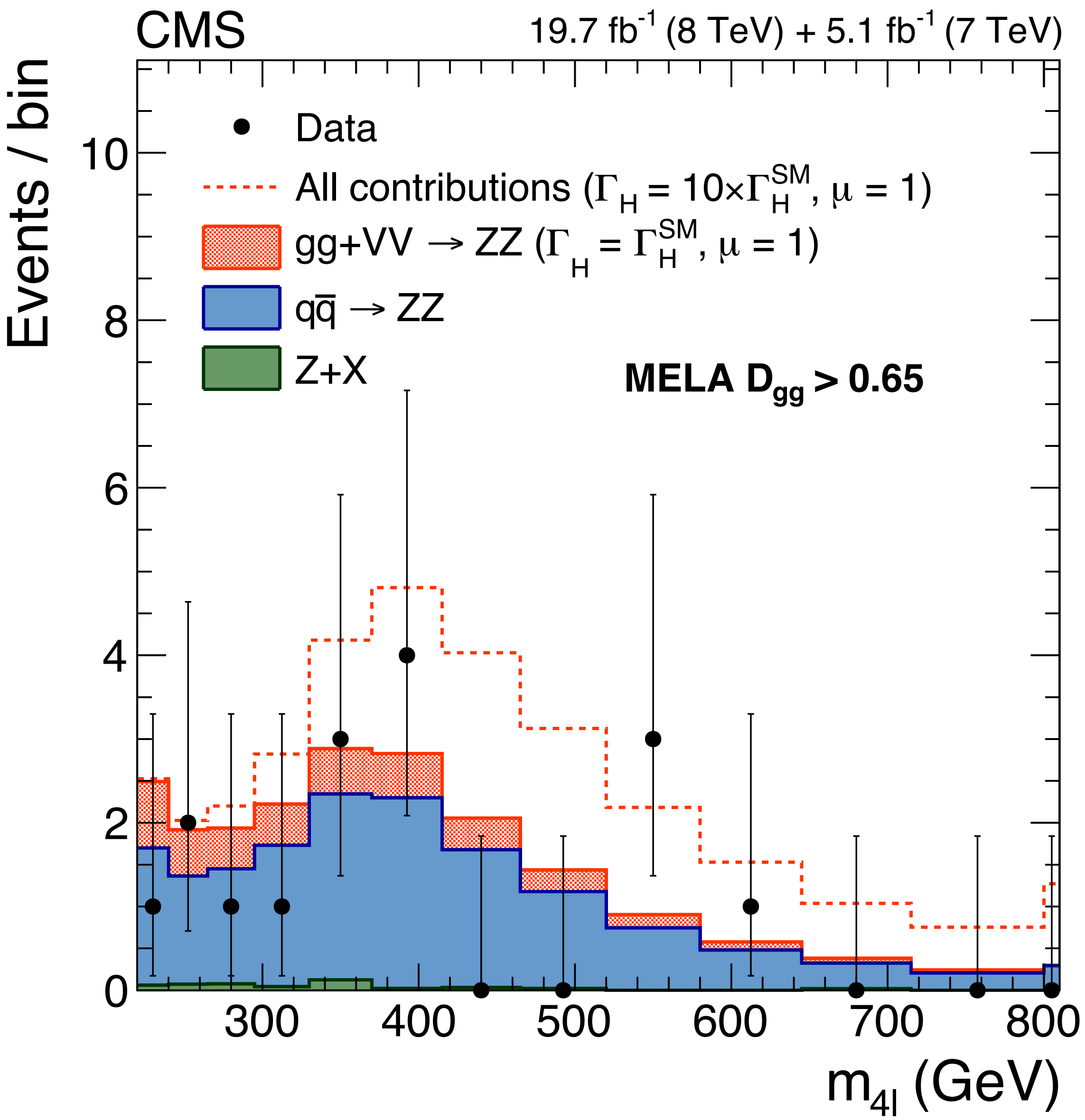
- Off the peak -> $N_{obs}^{off} \propto g_i^2 g_f^2 = \xi^4 g_{i,\mathrm{SM}}^2 g_{f,\mathrm{SM}}^2 \propto \xi^4 N_{\mathrm{SM}}^{off} = \frac{\Gamma_H}{\Gamma_{H,\mathrm{SM}}} N_{\mathrm{SM}}^{off}$

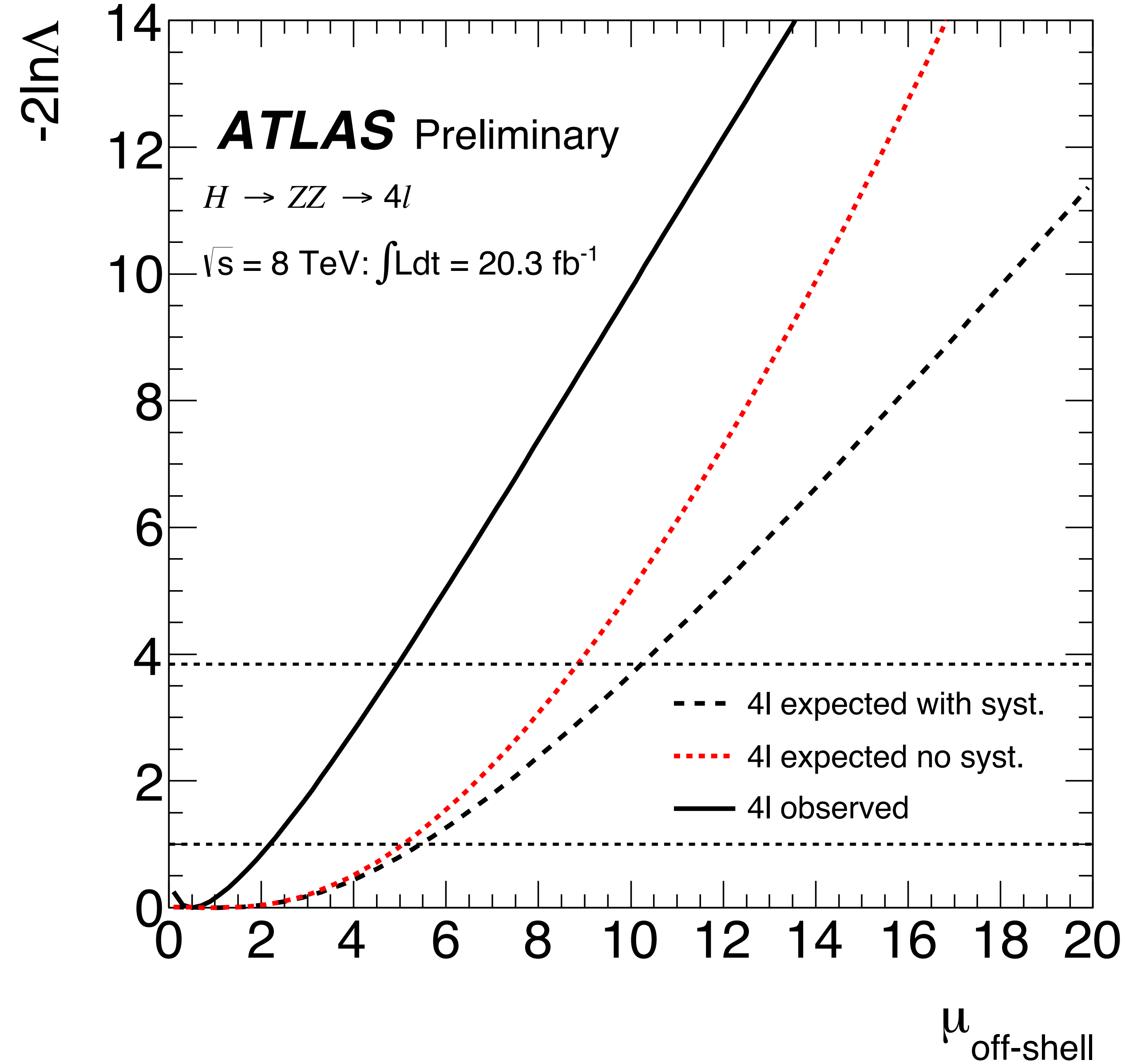
Bounds of the order ~ 10-20 $\Gamma_{H,SM}$ can be achieved

Refined tools available [Kauer (2008,2012); Ellis, Campbell, Williams (2013)]

Thorough phenomenological studies [Ellis, Campbell, Williams (2013)]

Analysis is doable (and actually done)





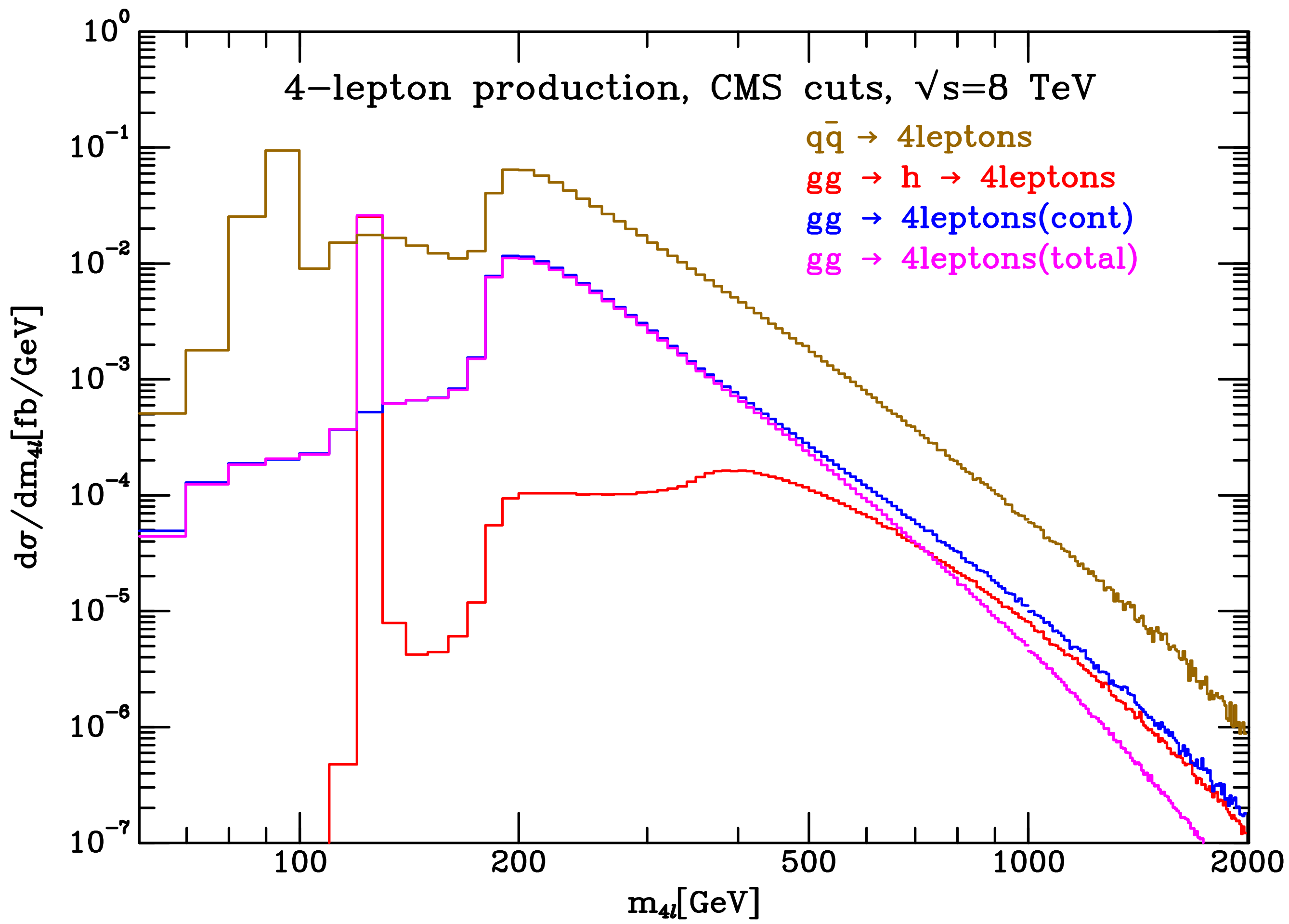
CMS: $\Gamma_H < 5.4\ \Gamma_{H,SM}$ = 22 MeV @ 95CL

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

With well-defined assumptions (see later)

Off-shell cross-section: work needs to be done

Method based on counting VV events in the high invariant-mass tail -> good prediction for 4l final state required



[Campbell, Ellis, Williams (2013)]

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

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

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

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

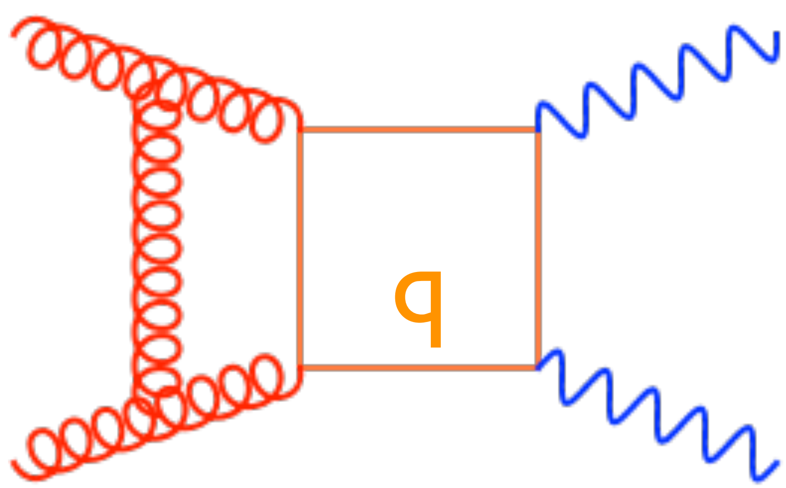
$$N_{\rm int} \sim -2 \times 10^{-2} N_{\rm tot}$$

Large (~uninteresting) qq contamination

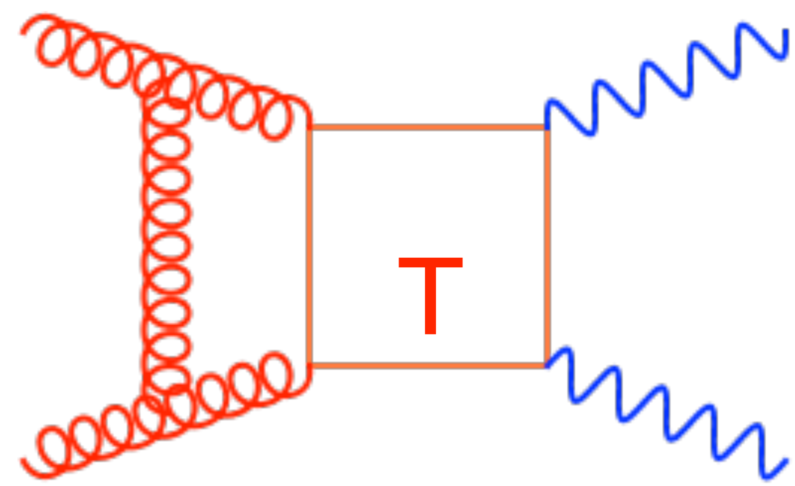
Delicate signal/background interference effects

Off-shell cross-section: work needs to be done

- qq/gg disentanglement (matrix element method very promising)
- First results for NNLO VV background are appearing-> thorough analysis achievable in the near future
- gg->VV background only known at LO (major drawback, large K-factor expected). Delicate S/B interference patterns



All ingredients recently computed



Complicated
Non-negligible / dominant in the off-shell tail

- until we know the exact result, estimates based on soft resummation -> thorough analysis for a 125 GeV Higgs should be performed

Off-shell cross-section: the interpretation issue

- Bounds on the width from off-shell cross-section based on relating couplings on and off-peak, assuming they do not change
- in QFT, couplings run
- for small (ie logarithmic) modification, the effect is negligible
- big effects can occur if strong modifications of the couplings occur, like for instance:
  - higher dimensional HVV operators
  - light d.o.f. running in the loops

In principle, such modifications are problematics for the interpretation of off-shell measurements.

- To what extent can be constrained by other measurements?
- What is the impact on off-shell measurements?
- How to parametrize / quantify these effects?

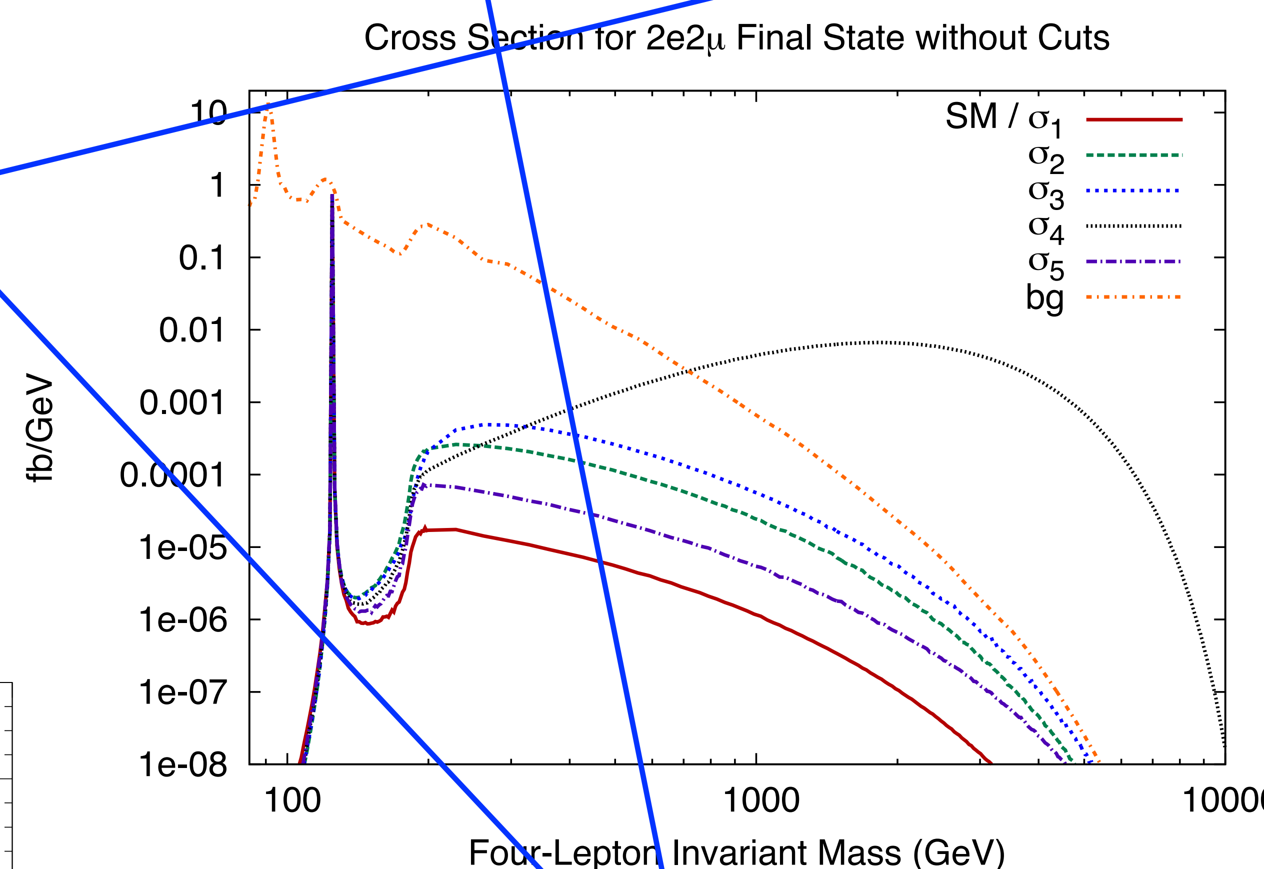
Example: anomalous HZZ coupling

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

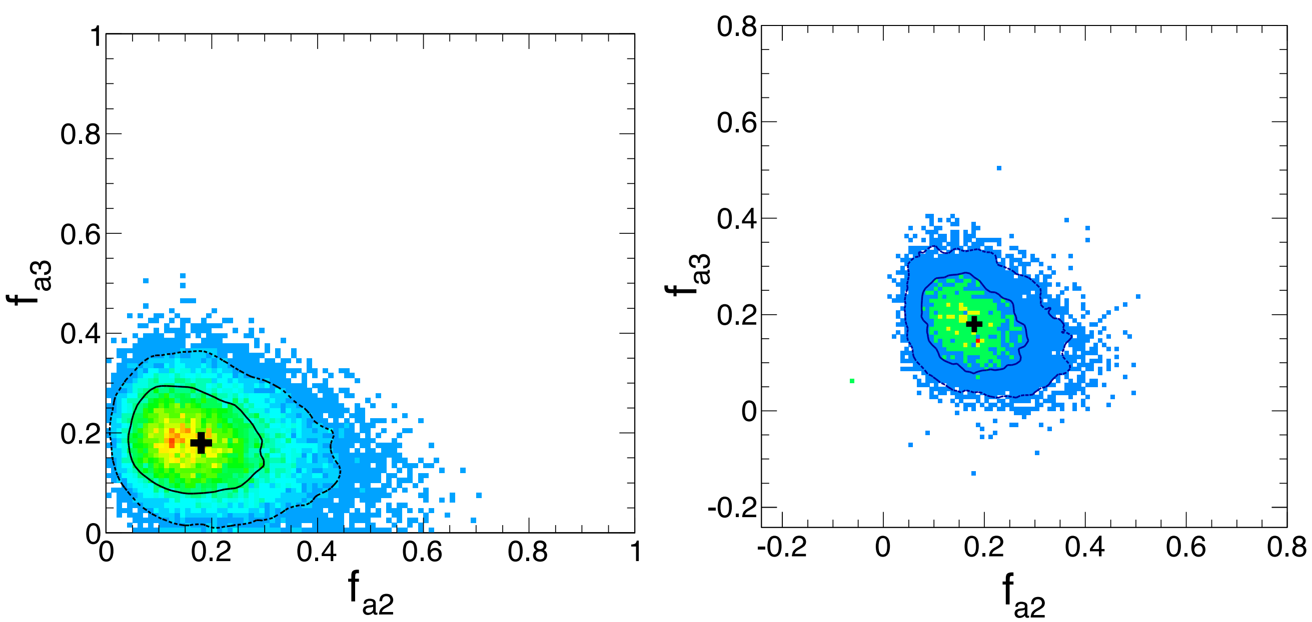
$$\mathcal{O}_1 = -\frac{M_Z^2}{v} H Z_\mu Z^\mu, \quad \mathcal{O}_2 = -\frac{1}{2v} H Z_{\mu\nu} Z^{\mu\nu} \quad \mathcal{O}_3 = -\frac{1}{2v} H Z_{\mu\nu} Z^{\mu\nu}, \quad \mathcal{O}_4 = \frac{2}{v} H Z_\mu \partial^2 Z^\mu$$

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

Modifications of the m_{4l} shape



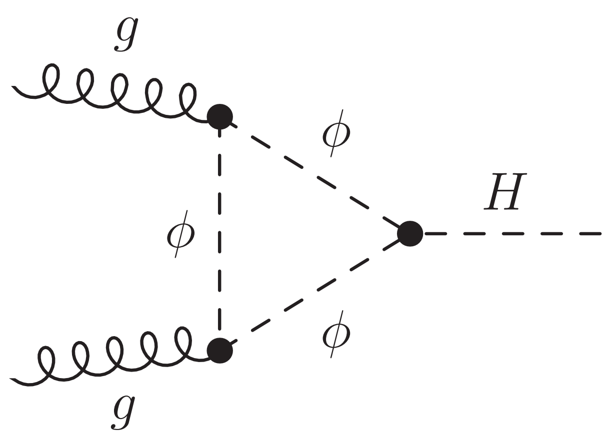
Modification of lepton angular distributions

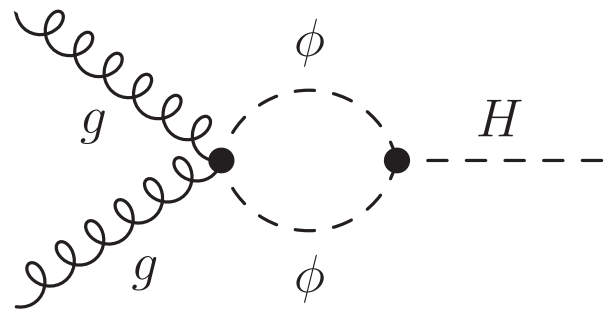


[Anderson et al. (2013)]

What is the constraining power for off-shell analysis?

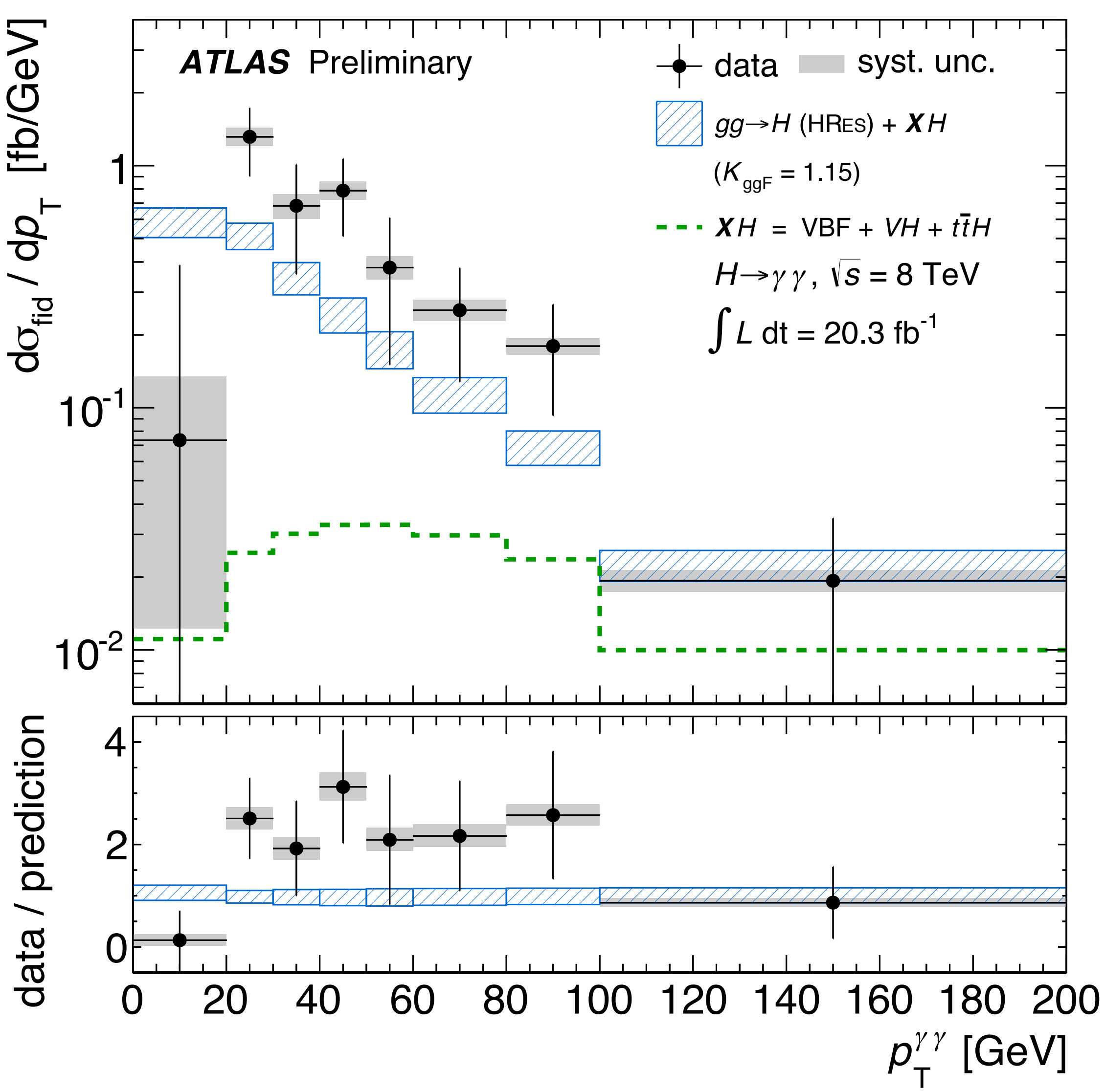
Example: light particles in the loop





[Englert, Spannowsky (2014)]

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



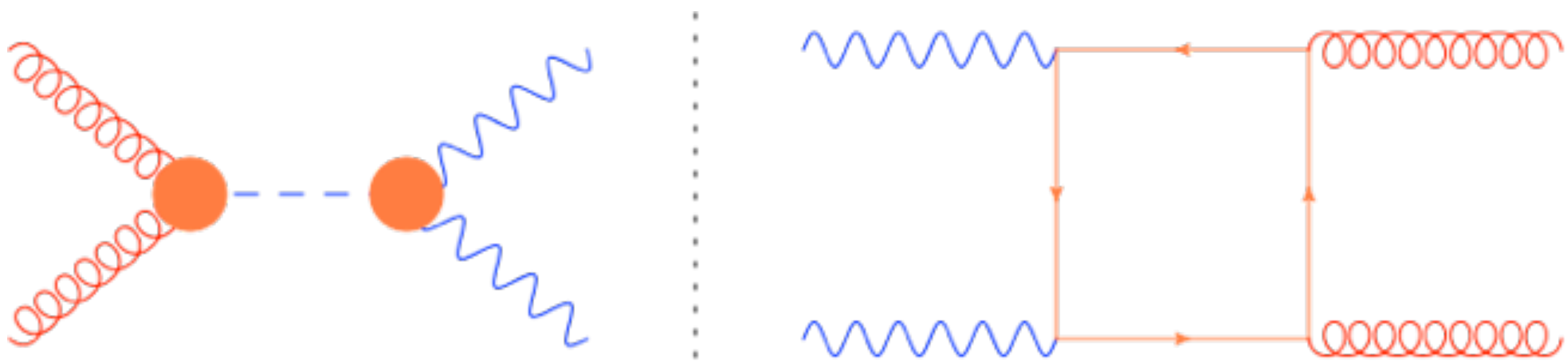
Will also affect other observables, e.g. Higgs p_T distributions
[Arnesen, Rothstein and Zupan (2008)]

- What is the constraining power of the Higgs p_T distribution on these kind of models? (need theoretical improvement, full m_t dependence)
- Can S/B interference enhancement give other constraints? (along the lines of [Dixon, Siu (2003)])

Other very interesting
‘non-traditional’ Higgs analysis:
Higgs properties from
interference effects

H-> γγ interference and the Higgs width

[Martin; Dixon, Li (2013)]



$g_i g_f$

$$A_{i\to f} = \frac{S m_h^2}{s - m_h^2 + i m_h \Gamma_h} + B$$

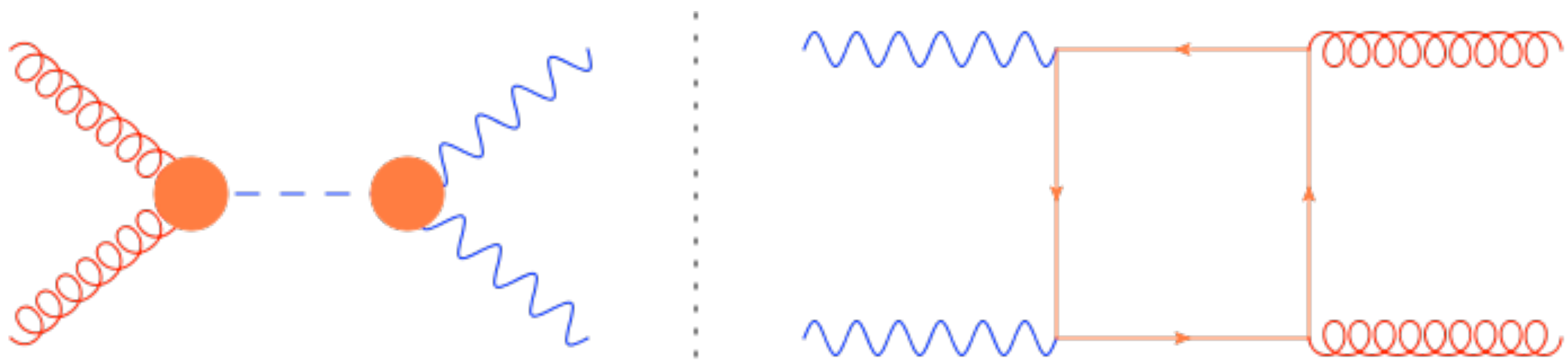
$$|A_{i\to f}|^2 = \frac{|S|^2 m_h^2}{(s-m_h^2)^2 + \Gamma_h^2 m_h^2}\left[1 + \frac{2(s-m_h^2)}{m_h^2}\mathrm{Re}\left(\frac{B^*}{S}\right) + \frac{2\Gamma_h}{m_h}\mathrm{Im}\left(\frac{B^*}{S}\right)\right] + |B|^2$$

$$\frac{g_i^2 g_f^2}{\Gamma_H}$$

$g_i g_f$

Knowledge of both on-peak and interference cross-section can disentangle coupling and BR -> independent extraction

Interference: the imaginary part and loop-enhancement



$$|A_{i\to f}|^2 = \frac{|S|^2 m_h^2}{(s-m_h^2)^2+\Gamma_h^2 m_h^2}\left[1+\frac{2(s-m_h^2)}{m_h^2}\mathrm{Re}\left(\frac{B^*}{S}\right)+\boxed{\frac{2\Gamma_h}{m_h}\mathrm{Im}\left(\frac{B^*}{S}\right)}\right]+|B|^2$$

- Interference loop enhanced (Signal -> 2 loop, Background-> 1 loop)

$$S\sim\frac{\alpha_s\alpha m_h^2}{(4\pi v)^2},\quad B\sim\frac{g_s^2 e^2}{(4\pi)^2}\qquad [\sigma_{\rm int}/\sigma_H]_{\rm naive}\approx\frac{2\Gamma_h}{m_h}\frac{(4\pi v)^2}{m_h^2}\approx 0.1$$

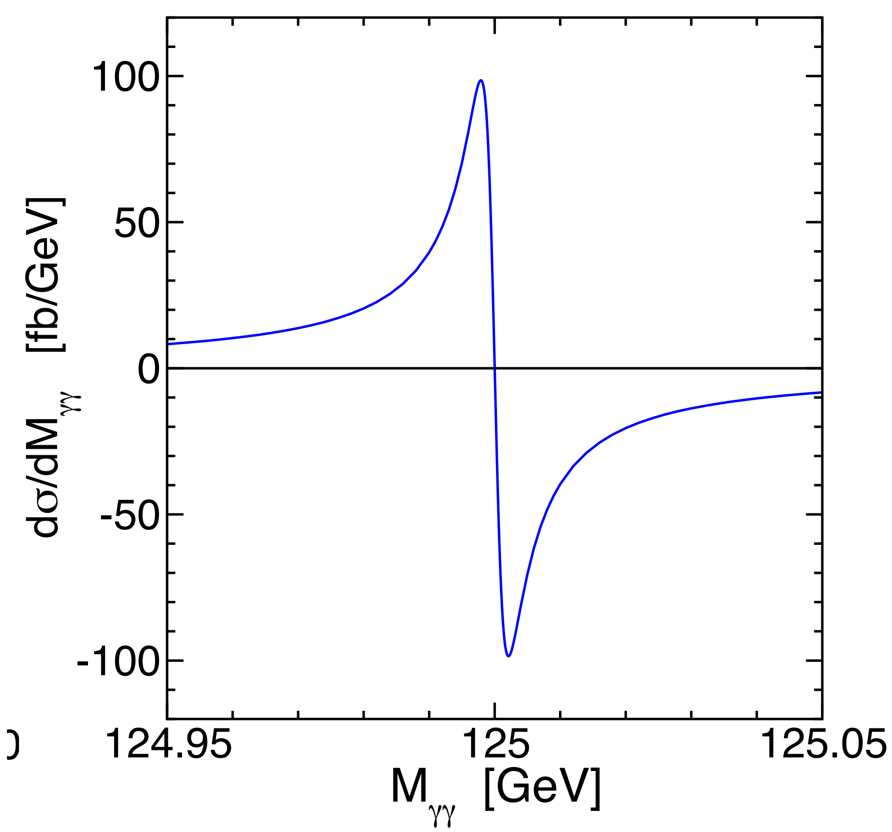
- Loop-enhancement not present in the SM (no ±± cut in the massless background amplitude, no cut in the top loop for m_H =125 GeV)
- Can be used to constrain light d.o.f. (-> non vanishing cut) in the Hgg coupling?

Interference: the real part and mass-shift

[Martin (2012); Dixon and Li; de Florian et al (2013)]

$$|A_{i\to f}|^2 = \frac{|S|^2 m_h^2}{(s-m_h^2)^2+\Gamma_h^2 m_h^2}\left[1+\frac{2(s-m_h^2)}{m_h^2}\mathrm{Re}\left(\frac{B^*}{S}\right)+\frac{2\Gamma_h}{m_h}\mathrm{Im}\left(\frac{B^*}{S}\right)\right]+|B|^2$$

$$\sigma_{off} \sim \frac{2\mathrm{Re}(SB^*)}{s-m_h^2}, \qquad (s-m_h^2) \gg m_h\Gamma_h$$



Create asymmetry in the $m_{\gamma\gamma}$ distribution

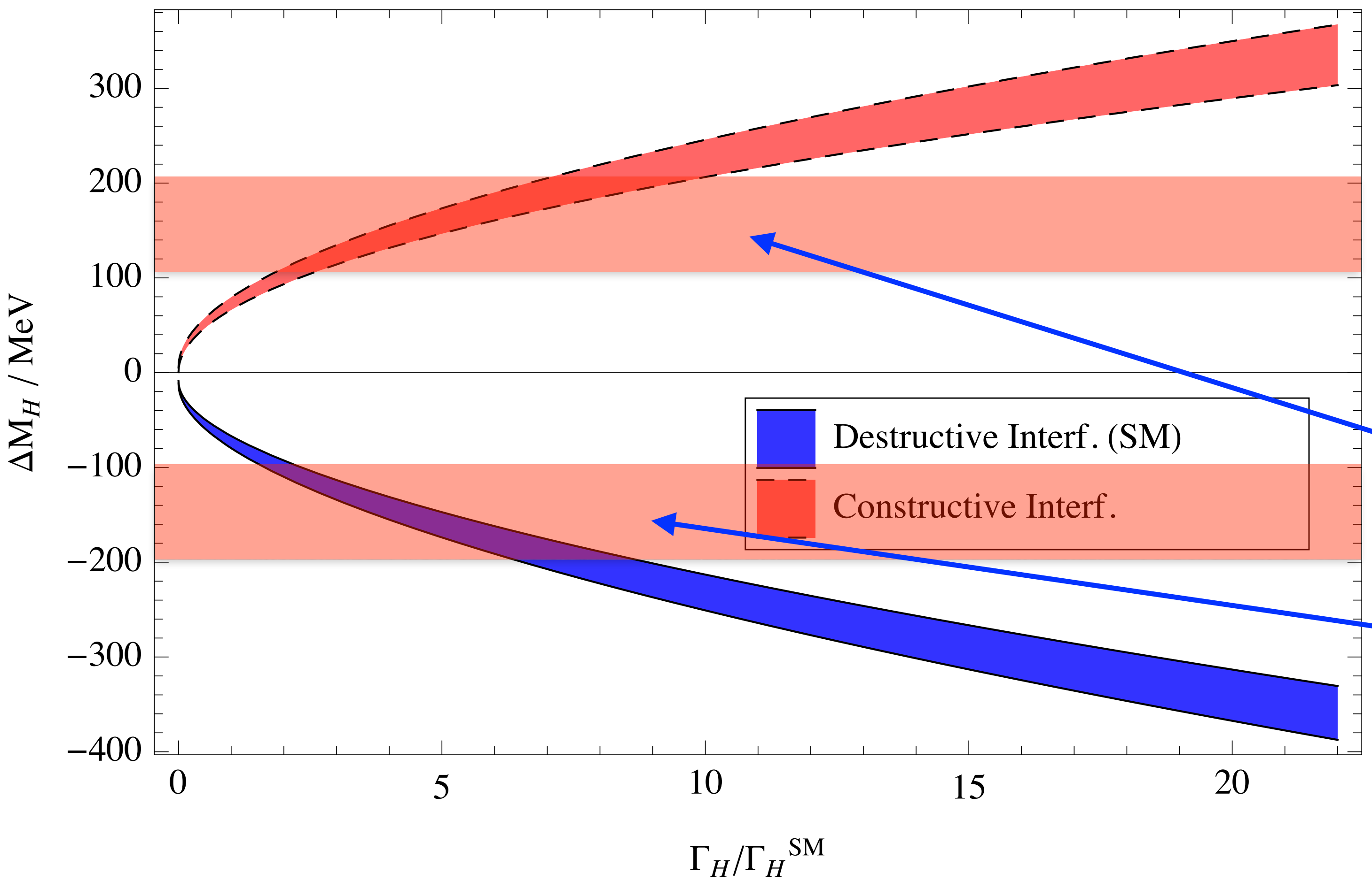
- asymmetric -> irrelevant for σ
- however, it leads to mass-shift in the γγ channel

Independent on Γ_H -> in combination with on-shell measurements, allows for independent width / coupling extraction

$\Delta M_{ZZ,\gamma\gamma}$: model-independent determination of Γ_H

[Dixon and Li (2013)]

Comparing mass determination in the γγ with control mass (e.g. ZZ) ⟶ $\delta m_H \approx -100\ \mathrm{MeV} \times \sqrt{\Gamma_H/\Gamma_{H,\mathrm{SM}}}$



Theory in pretty good shape
[Dixon and Li; de Florian et al (2013)]

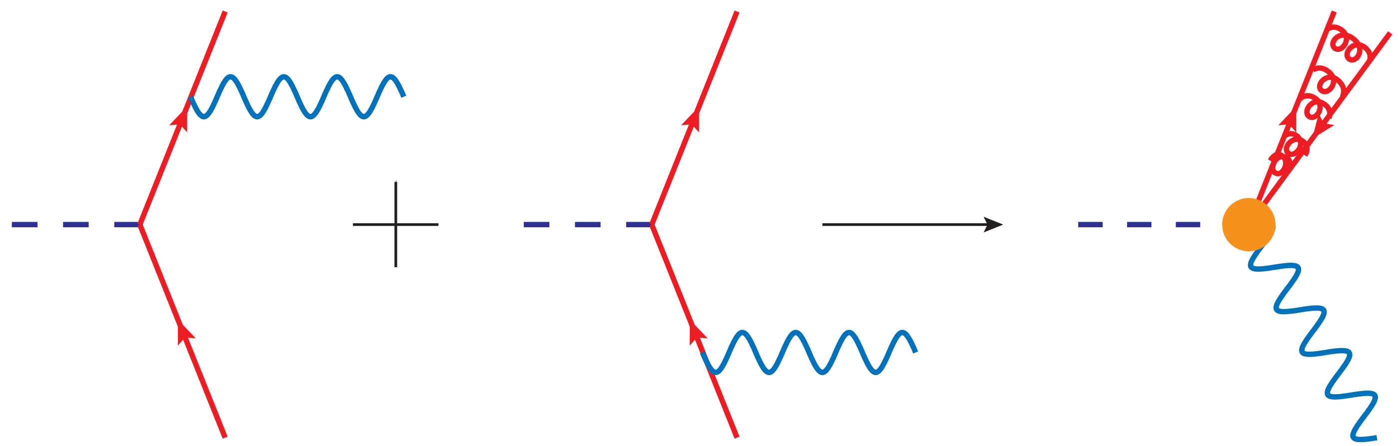
ultimate LHC reach?

- How well can ATLAS/CMS measure the mass-shift?
  (both in the near future and in the long term)
- What can we say about non-standard Higgs? [Dixon et al]

H-> J/Ψ interference and the Hcc coupling

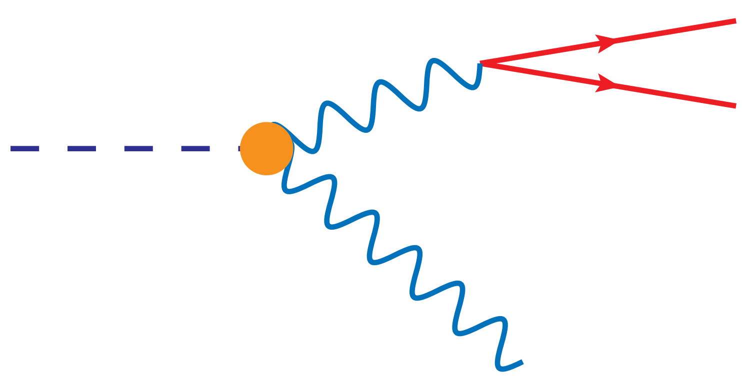
[Bodwin, Petriello et al (2013)]

Interference of two 'signal' amplitudes for
H -> quarkonium and photon can constrain the Hcc coupling



Direct component

- depends on Hcc coupling
- small



Fragmentation component

- does not depend on Hcc coupling
- large

Large (negative) interference leads to enhancement of the small direct amplitude -> access to Hcc

Which kind of constraints on Hcc at the (high-lumi) LHC?

Matrix element method (MEM)

(kinematic discriminant used by MCFM authors)

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

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

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

P_H : gg induced Higgs amplitude squared

CMS analysis

improvements on phenomenological studies:

- 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 ($P_H \rightarrow P_{gg}$), backgrounds fully considered

ATLAS analysis

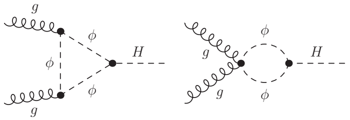
improvements:

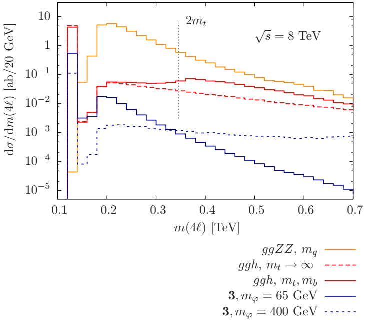
- similar to CMS, thorough consideration of systematic uncertainties
- provide results as function of the unknown $gg \rightarrow ZZ$ background K-factor, variation: $[0.5, 2] \times$ signal K-factor
- off-shell signal strength in $[5.6, 9.0]$ ($[6.6, 10.7]$ expected)

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)

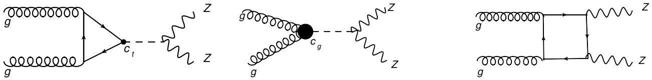




C. Englert, M. Spannowsky (2014)

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))

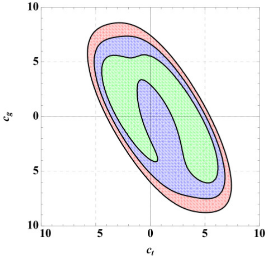


$$\mathcal{L} = -c_t \frac{m_t}{v} \bar{t}th + \frac{g_s^2}{48\pi^2} c_g \frac{h}{v} G_{\mu\nu}G^{\mu\nu}$$

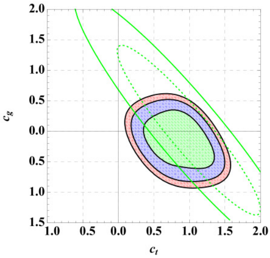
$$\mathcal{M}_{gg\to ZZ} = \mathcal{M}_h + \mathcal{M}_{bkg} = c_t\,\mathcal{M}_{c_t} + c_g\,\mathcal{M}_{c_g} + \mathcal{M}_{bkg}$$

$\sigma \sim |c_t + c_g|^2$: 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 MEM improved!)



LHC 8 TeV CMS data



LHC 14 TeV 3 ab^{-1} data

Summary

• ggF and VBF off-shell $H \to ZZ, WW$ data at (HL-)LHC and (I)LC ($\to$ S. Liebler) facilitates novel, complementary approach to constrain Higgs properties (width, coupling strength and structure)

• complementary method (by S.P. Martin): $gg \to H \to \gamma\gamma$ signal background interferometry (Higgs mass peak shift depending on Γ_H)

• also: $Hc\bar{c}$ constraint via signal-signal interferometry after HL-LHC (G.T. Bodwin, F. Petriello, S. Stoynev, M. Velasco)

• Higgs width constraints: limited model independence in ggF (but $\sim\mathcal{O}(1)\,\Gamma_{H,\text{SM}}$ bounds after LHC Run 1); largely model independent in VBF as well as $gg \to H \to \gamma\gamma$ interferometry (but needs HL-LHC, (I)LC for $\sim\mathcal{O}(1)\,\Gamma_{H,\text{SM}}$ bounds)

• further exploration of feasible off-shell/interference-enabled constraints in SM, via EFT or specific BSM at LHC Run1,2,3,HL and ILC; further discussion of model dependence issues and value added compared to on-shell Higgs measurements

• theoretical tools: full NLO calculation for $gg \to (H \to)\,\gamma\gamma$ (L. Dixon, Y. Li); but only LO calculations (with finite t, b mass effects) for $gg \to (H \to)\,4$ leptons interference and continuum background contributions plus event generators (also for qg?), large K-factor expected (soft-collinear approx.), but full NLO calculation is pushing current technology (bottleneck: heavy quark loop), easier: soft-resummation-improved predictions; further discussion of available tools, included higher order corrections, estimation of residual uncertainties and future calculational progress

• analysis techniques: improvements via MEM, optimal kinematic discriminants (sensitivity?)