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

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thanks to Heather Logan for providing a slide

8th Workshop of LHC Higgs Cross Section Working Group
CERN
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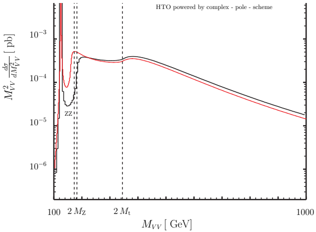
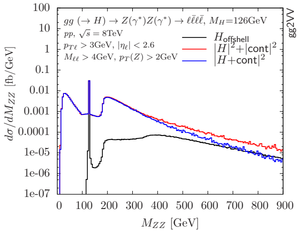
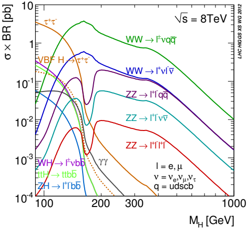
Outline

- Standard Model: physics, calculations and tools
- $H \to ZZ, WW$ in ggF & VBF: sizeable off-shell Higgs signal contribution with large signal-backg. interference
- off-shell Higgs boson signal strength & novel Higgs width bound, "pioneering" CMS & ATLAS analyses $\longrightarrow$ Yanyan's talk
- Higgs width bounds from $gg \to H \to \gamma\gamma$
- Beyond the Standard Model
- model dependence of the Higgs width bound
- Exploiting the high-mass $H \to ZZ$ region: EFT
- Studying the high-mass $H \to ZZ$ region: BSM benchmark scenarios
- Off-shell task force meetings
- YR4 projects

$gg \to H \to ZZ, WW$: sizeable off-shell Higgs signal with large signal-background interference







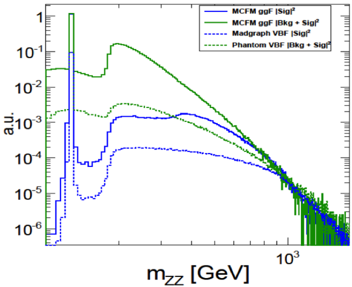
- $gg \to H \to VV \to 4\ell$ and $2\ell 2\nu$ signal-background interference very well studied at LO:

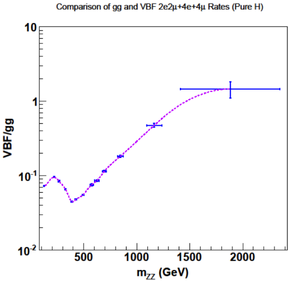
Glover, van der Bij (1989); Kao, Dicus (1991); Binoth, Ciccolini, NK, Krämer (2006) (gg2WW); Campbell, Ellis, Williams (2011) (MCFM); NK (2012) (gg2VV); NK, Passarino (2012); Campanario, Li, Rauch, Spira (2012); Bonvini, FC, Forte, Melnikov, Ridolfi (2013); FC, Melnikov (2013); NK (2013) (gg2VV); Campbell, Ellis, Williams (2013) (MCFM); Campbell, Ellis, Williams (2014) (MCFM); Campbell, Ellis, Furlan, Röntsch (2014); related interference effects: Bredenstein, Denner, Dittmaier, Weber (2006) (PROPHECY4f); YR3: Denner, Dittmaier, Mück (2013) and Anderson, Bolognesi, FC, Gao, Gritsan, Martin, Melnikov, Schulze, Tran, Whitbeck, Zhou (2013); Chen, Cheng, Gainer, Korytov, Matchev, Milenovic, Mitselmakher, Park, Rinkevicius, Snowball (2013); Chen, Vega-Morales (2013)

- tools for ggF: MCFM-6.8, gg2VV-3.1.7 (parton-calculators and LO event generators)
- loop technology closing in on NLO calc. (bottleneck: heavy quark loop) Zurich, Karlsruhe, FNAL-RWTH, ...
- gluon-fusion Higgs production and semileptonic decay: Dobrescu, Lykken (2010); Lykken, Martin, Winter (2012); Kao, Sayre (2012); ATLAS arXiv:1206.2443; ATLAS arXiv:1206.6074; CMS PAS HIG-13-008

Sizeable off-shell Higgs signal in vector boson fusion

- similar effect in VBF $H \to VV$ (NK, Passarino): $\mathcal{O}(10\%)$ of Higgs signal is off-shell
  note: no exp. sensitivity to off-shell $H \to VV$ tail in VH and $t\bar{t}H$ channels (see $\sigma_{\text{prod}}(M_H)$)
- total off-shell Higgs signal has $\sim 10\%$ VBF contribution





Covarelli, Anderson, Sarica

figures taken from Covarelli's talk at LHC HXSWG workshop (12 Jun 2014)

- tools for VBF: MadGraph5 Alwall et al., Phantom Ballestrero et al., VBFNLO Baglio et al.

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, et al. (2013,...), SFitter
- $e^+e^- \rightarrow Z(H \rightarrow$ 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

Higgs width determination and off-resonance signal

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

FC, 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"): $\boxed{\sigma_{i\to H\to f} \overset{\text{NWA}}{\propto} \frac{g_i^2 g_f^2}{\Gamma_H}}$

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

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

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

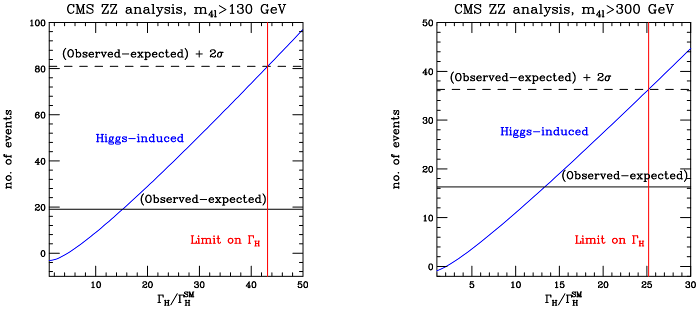
sizeable off-resonance contribution to signal cross section is independent of Higgs width, and therefore "breaks" NWA scaling degeneracy: $\sigma_{\text{off-peak}}/\sigma_{\text{on-peak}} \propto \Gamma_H$

MCFM analysis

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

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

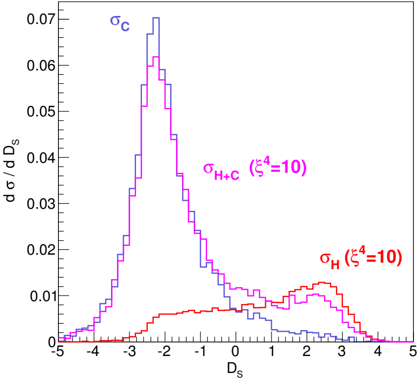
$P_{q\bar{q}}$: $q\bar{q}$ induced continuum background

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

P_H : gg induced Higgs amplitude squared

Discriminant:

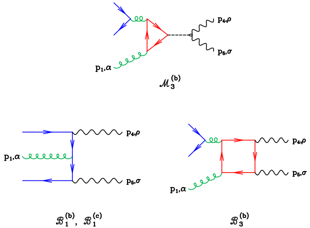
$$D_S = \log\left(\frac{P_H}{P_{gg} + P_{q\bar{q}}}\right)$$

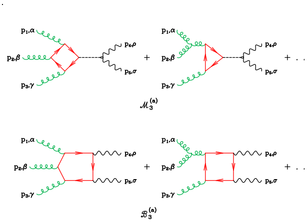


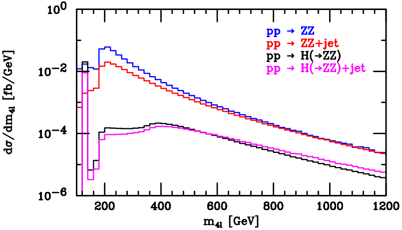
$\Gamma_H < \left(15.7^{-2.9}_{+3.9}\right) \Gamma_H^{SM}$ (95% CL), $(D_S > 1)$

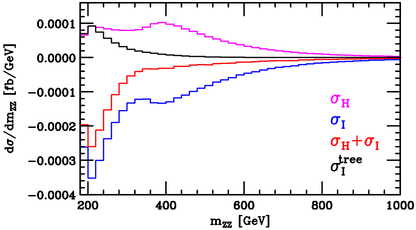
bound $1.6 \times$ better than for $m_{4\ell} > 300$ GeV

Interference for $pp \to H \to ZZ$ + jet









off-shell Higgs cross sections for ZZ and ZZ+jet comparable ($p_{Tj} > 30$ GeV)

Campbell, R.K. Ellis, Furlan, Röntsch   figures taken from arXiv:1409.1897

Z bosons treated in zero-width approximation (validated for ZZ final state: excellent for $m_{4l} > 300$ GeV)

VBF off-shell Higgs signal and LHC Higgs width bound

Dedicated VBF study for $H \to ZZ \to 4\ell$ Englert, Spannowsky

VBF selection cuts are applied, which essentially remove ggF contribution:

$$p_T(j) > 20 \text{ GeV}, \ \Delta R(jj) \geq 0.6, \ |y_j| < 4.5,$$

$$\Delta y(jj) \geq 4.5, \ y_{j_1} \times y_{j_2} < 0, \ m(jj) \geq 800 \text{ GeV},$$

$$\Delta R(\ell j) \geq 0.6, \ \text{all } \ell \text{ inside the tagging jets' rapidity gap},$$

and a jet veto: $|y_j^{\text{veto}}| < 2.5, \ p_T^{\text{veto}}(j) > 50 \text{ GeV}, \ \Delta y(j_{\text{veto}} j) > 0.3$

Off-shell signal: σ_H(VBF selection, $m_{4\ell} \geq 130$ GeV, $\ell = e, \mu$) $\simeq$ 0.04 fb at 14 TeV

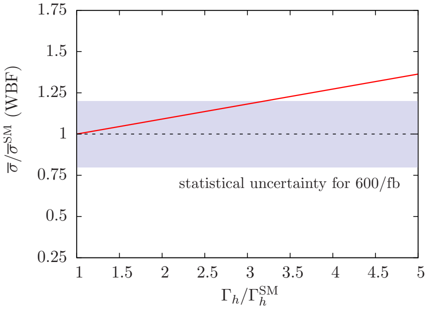
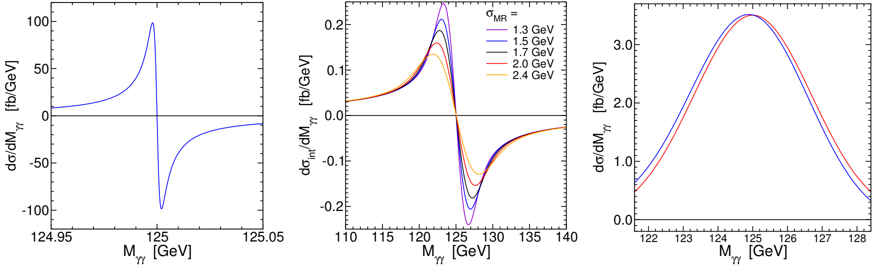


figure taken from arXiv:1405.0285

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})

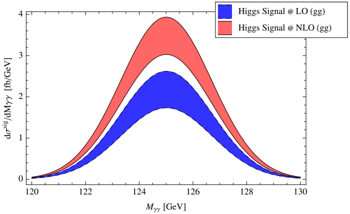
right fig.: peak shift of invariant mass distribution ($\sigma_{\text{MR}} = 1.7$ GeV): $\Delta M_{\gamma\gamma} = -120$ MeV at LO

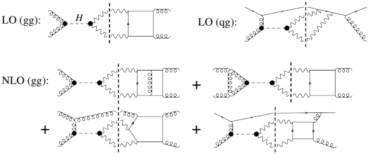
$(H \to \gamma\gamma)$+jet at LO: negligible mass peak shift (< 20 MeV for $p_{Tj} > 25$ GeV)

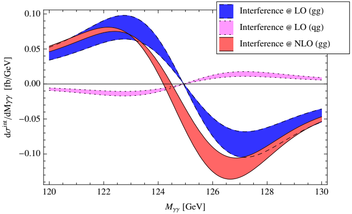
Daniel de Florian, et al. (2013); S. Martin (2013)

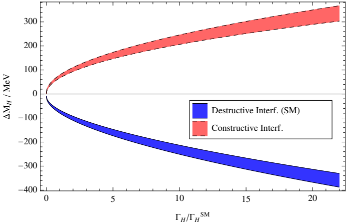
Higgs width via interferometry in $H \to \gamma\gamma$

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









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

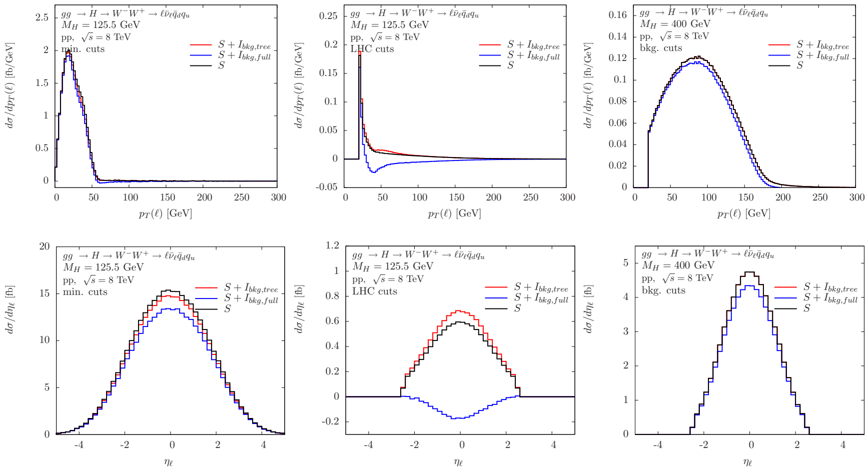
Vary Higgs width and couplings (maintaining on-peak SM signal strenghts):

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

$gg \to H \to VV \to f\bar{f}f\bar{f}$: signal-background interference @ LO

validate automatic tools (MG5_aMC@NLO, Sherpa+OpenLoops) with custom calculations

Example: Interference for semileptonic H decay modes in ggF

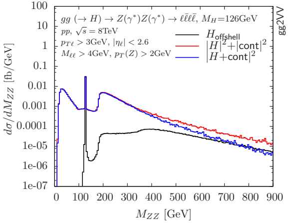


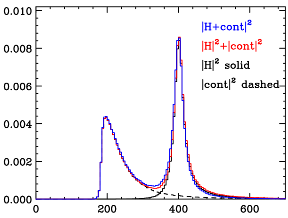
NK, C. O'Brien, E. Vryonidou   gg2VV and MG5_aMC@NLO

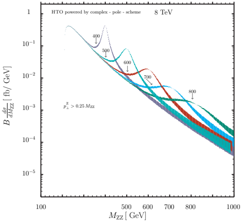
Heavy Higgs - light Higgs - continuum interference

consider a heavy Higgs h_2 (signal) in addition to a light Higgs h_1 at 125 GeV (background)

Two-Higgs model: SM & real EW singlet scalar, as defined in YR3 arXiv:1307.1347, Sec. 13.3







right fig.: G. Passarino (arXiv:1206.3824)

What is the impact of interference with the offshell tail of the 125 GeV Higgs for a heavy Higgs of 300, 600 or 900 GeV?

$$S \sim |\mathcal{M}_{h2}|^2$$

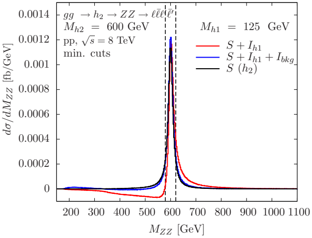
$$I_{h1} \sim 2\,\mathrm{Re}(\mathcal{M}^*_{h2}\,\mathcal{M}_{h1})$$

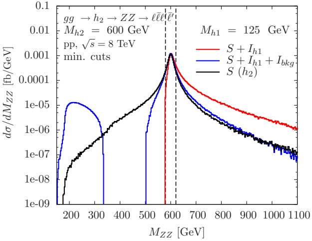
$$I_{bkg} \sim 2\,\mathrm{Re}(\mathcal{M}^*_{h2}\,\mathcal{M}_{bkg})$$

$$I_{full} \sim 2\,\mathrm{Re}(\mathcal{M}^*_{h2}\,(\mathcal{M}_{h1} + \mathcal{M}_{bkg}))$$

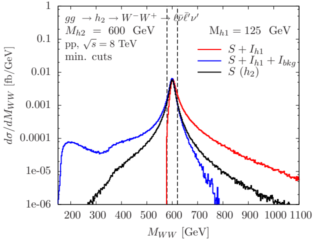
Two-Higgs model details: $\theta = \pi/8$ ($\sigma_{h1} \approx \sigma_{H,\mathrm{SM}}$ up to 20%), $\Gamma_{h1} = 4.2577 \cdot 10^{-3}$ GeV for $M_{h1} = 125$ GeV, $\Gamma_{h2} = 1.70204\ (20.7236)\ [69.1805]$ GeV for $M_{h2} = 300\ (600)\ [900]$ GeV

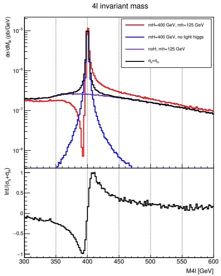
Heavy Higgs - light Higgs - background interference

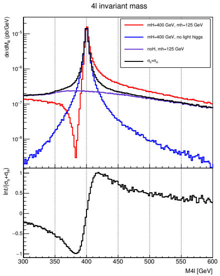




NK, C. O'Brien Higgs Higgs (N)NLO MC and Tools Workshop for LHC RUN-2 (2014)







NK, C. O'Brien

E. Maina heavy/light interf.; $s_\alpha = 0.2$ (left) 0.3 (right), 1501.02139

Beyond the Standard Model

Constraining higher dimensional operators with the off-shell Higgs

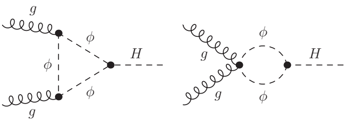
Limitations of model-independence, but complementary constraints possible:

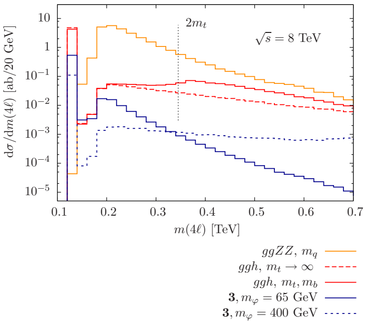
lept. angular correlations, $M_{4\ell}$ shape (1309.4819), Higgs p_T (0809.1429), boosted Higgs (1410.5806)

Disentangling New Physics with the off-shell Higgs boson

EFT studies including the off-shell Higgs boson

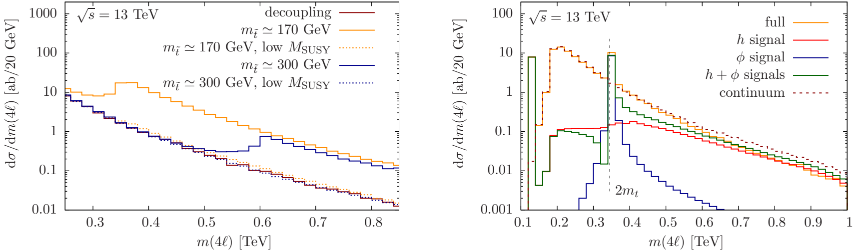
J. Gainer, J. Lykken, K. Matchev, S. Mrenna, M. Park (2014); C. Englert, M. Spannowsky (2014); M. Ghezzi, G. Passarino, S. Uccirati (2014); G. Cacciapaglia, A. Deandrea, G. Drieu La Rochelle, J. Flament (2014); A. Azatov, C. Grojean, A. Paul, E. Salvioni (2014); A. Biekoetter, A. Knochel, M. Kraemer,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





C. Englert, M. Spannowsky (2014) (1405.0285)

BSM benchmark scenario studies

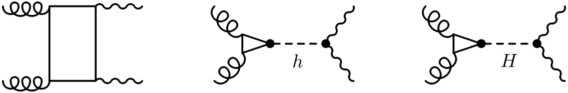


left: MSSM, right: portal-extended SM model

C. Englert, Y. Soreq, M. Spannowsky (2014) (1410.5440)

Loophole: additional light scalar in the s-channel

[H.E. Logan, 1412.7577]



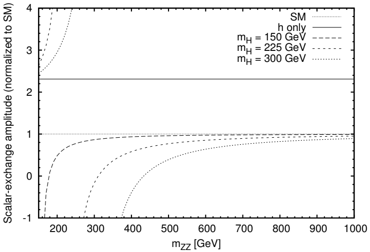
SM: h cancels growth $\propto E/v$ of $t\bar{t} \to ZZ$ amplitude.

Modified h couplings: cancellation imperfect; growth of amplitude with E provides LHC sensitivity at high m_{ZZ}!

Extended Higgs sector: Require $\kappa_t^h \kappa_Z^h + \kappa_t^H \kappa_Z^H = 1$ for unitarity of $t\bar{t} \to ZZ$ (automatic in renormalizable models): $\kappa_t^h \kappa_Z^h = 1 + \Delta > 1, \quad \kappa_t^H \kappa_Z^H = -\Delta$

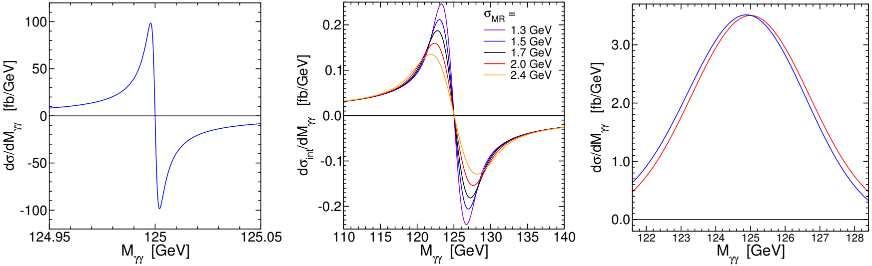
Amplitude relative to SM:

$$\begin{aligned} \frac{\mathcal{M}_h + \mathcal{M}_H}{\mathcal{M}_{h_{\rm SM}}} &= (1+\Delta) - \Delta \frac{p^2 - m_h^2}{p^2 - m_H^2} \\ &\simeq 1 - \Delta \frac{(m_H^2 - m_h^2)}{p^2} \\ &\to 1 \text{ for } p^2 \gg m_{h,H}^2 \end{aligned}$$



Presence of H at low mass (well below 350 GeV) causes $gg \to ZZ$ cross section to be SM-like at high m_{ZZ}, even if $\kappa_t^h \kappa_Z^h$ is strongly non-SM-like.

BSM dependence of $H \to \gamma\gamma$ mass peak shift?



Higgs resonance - BSM continuum interference effects?

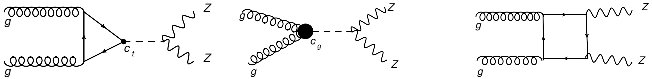
new feature: BSM EW light degrees of freedom active in loop-induced $H \to \gamma\gamma$ decay?

VBF-enriched $H \to \gamma\gamma$ “SM-like” study in progress L. Dixon, Y. Li, S. Höche

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 (PRL 2014))

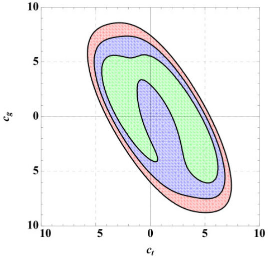


$$\mathcal{L} = -c_t \frac{m_t}{v} \bar{t}th + \frac{g_s^2}{48\pi^2} c_g \frac{h}{v} G_{\mu\nu}G^{\mu\nu}$$

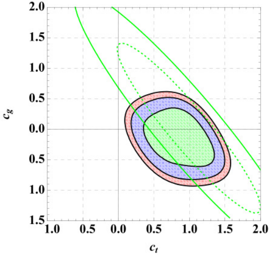
$$\mathcal{M}_{gg\to ZZ} = \mathcal{M}_h + \mathcal{M}_{bkg} = c_t \mathcal{M}_{c_t} + c_g \mathcal{M}_{c_g} + \mathcal{M}_{bkg}$$

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

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

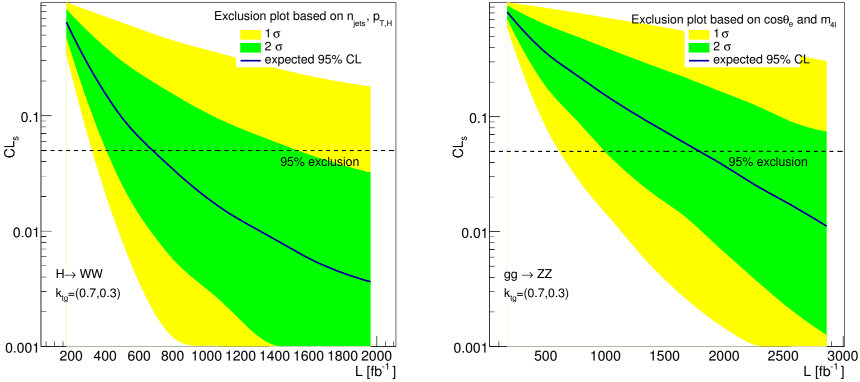


LHC 8 TeV CMS data



LHC 14 TeV 3 ab^{-1} data

Effective ggH coupling: boosted v. off-shell Higgs sensitivity



left: boosted analysis, right: off-shell analysis (not MELA improved)

M. Buschmann, D. Goncalves, S. Kuttimalai, M. Schoenherr, F. Krauss, T. Plehn (2014) (1410.5806)

Off-shell task force meetings

1. A HXSWG open meeting on off-shell and sig-bkg interference issues took place on 24th October 2014 with the following invited presentations:
    - Off-shell Higgs interference effects and width measurements in the ZZ decay channel, Raoul Rontsch (Fermilab)
    - EFT analysis of the off-shell Higgs data, Aleksandr Azatov (CERN)
    - MC tools: MadGraph5_aMC@NLO status report, Fabio Maltoni (Louvain)
    - MC tools: Sherpa+OpenLoops status report, Frank Krauss (IPPP Durham)
    - Interference effects in diphoton production for VBF, Nerina Fidanza (Buenos Aires)
    - Rare Higgs decays as probes for Higgs couplings to first- and second generation quarks, Stoyan Stoynev (Northwestern)
2. WG1 off-shell & WG2 Skype discussion on 13 January 2015 regarding kappa-framework extension to off-shell vs. EFT and BSM benchmark studies (to be continued at 22-24 January meeting at CERN and 3. meeting, see next)
3. WG1 off-shell & WG2 & WG3 virtual meeting to discuss model aspects of off-shell studies
   time: first week of February
   Doodle poll link: http://doodle.com/wdbuki378vi8fdfs

YR4 projects

- validation of automatised (event) generation for all $gg\ (\to H) \to VV \to f\bar{f}f\bar{f}$ processes at LO
- work on tools for $pp\ (\to H) \to VV$+jet(s) at NLO incl. gg-type at LO and PS merging (Sherpa+OpenLoops, 1309.0500)
- NLO $gg \to ZZ, WW$ calculation (with finite quark mass effects)
- NNLO $pp \to VV$ tools
- ggF & VBF heavy Higgs searches (interference effects)
- anomalous off-shell coupling studies (discuss further with WG2)
- additional high-mass ZZ EFT studies (discuss further with WG2)
- studies for BSM benchmark scenarios (discuss with WG3)
- automatised tools for EFT and BSM benchmark analyses
- enhanced analysis techniques (Where is MEM crucial? Are kinematic discriminants optimal? Estimation of residual uncertainties.)
- enhanced $H \to \gamma\gamma$ peak shift analysis & model dependence studies
- thorough assessment of what value is added by off-shell/interference enabled Higgs analyses compared to on-shell analyses is desirable in the medium term