# HXSWG Off-shell and interference subgroup: Theory update

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# YR4 chap.: *Off-shell Higgs Production and Higgs Interference*

finalised version (51 p.) $\longrightarrow$ session materials

I.8.3 $H \to VV$ modes ($V = W, Z$)

I.8.3.1 Input parameters and recommendations for the QCD scale and the order of the gluon PDF

I.8.3.2 Off-shell and interference benchmark cross sections and distributions: Standard Model

I.8.3.3 Off-shell and interference benchmark cross sections and distributions: 1-Higgs Singlet Model

I.8.3.4 Multijet merging effects in $gg \to \ell\bar{\nu}_\ell \bar{\ell}'\nu_{\ell'}$ using SHERPA

I.8.3.5 Study of higher-order QCD corrections in the gg→H→VV process

I.8.3.6 Higgs boson off-shell simulation with the MCFM and JHU generator frameworks

I.8.3.7 Interference contributions to gluon-initiated heavy Higgs production in the 2HDM using GOSAM

I.8.4 $gg \to VV$ at NLO QCD

I.8.4.1 The status of theoretical predictions

I.8.4.2 Brief description of the NLO computation for $gg \to 4l$

I.8.4.3 Results and recommendation for the $gg\ (\to H) \to ZZ$ interference $K$-factor

I.8.5 $H \to \gamma\gamma$ mode

I.8.5.1 Theory overview

I.8.5.2 Monte Carlo interference implementations

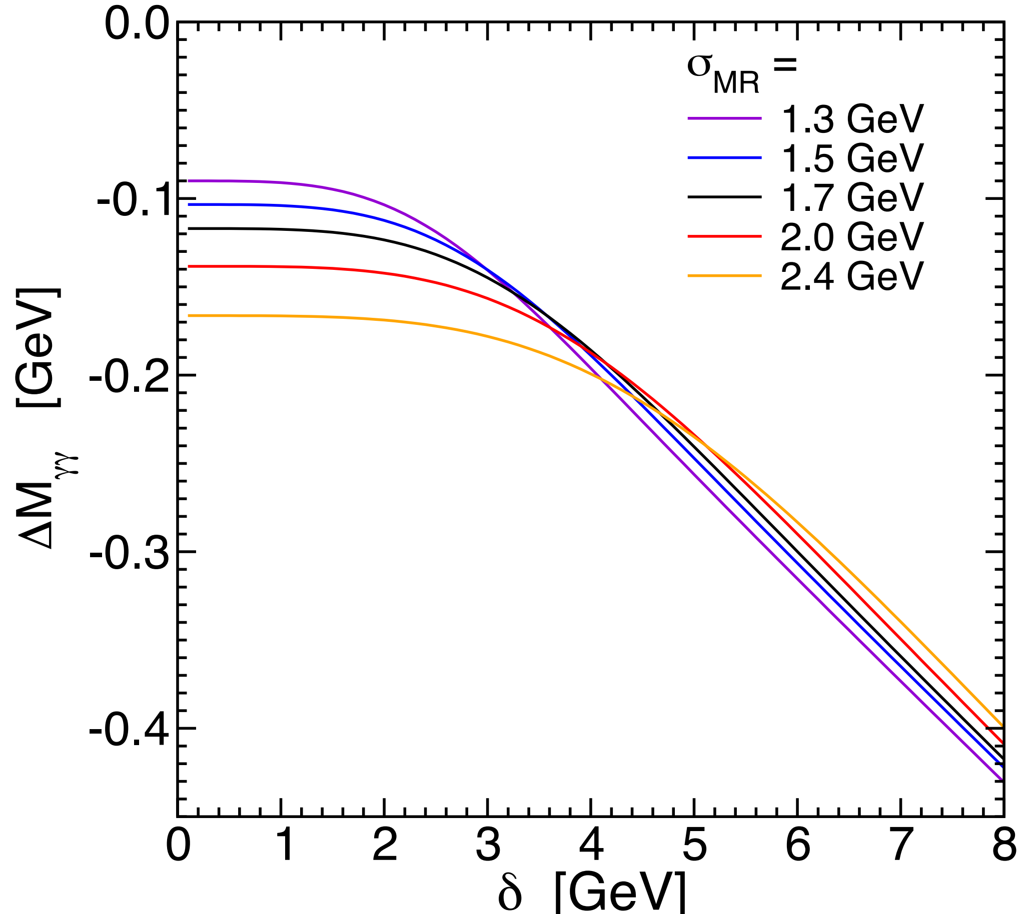
I.8.5.3 Studies from ATLAS

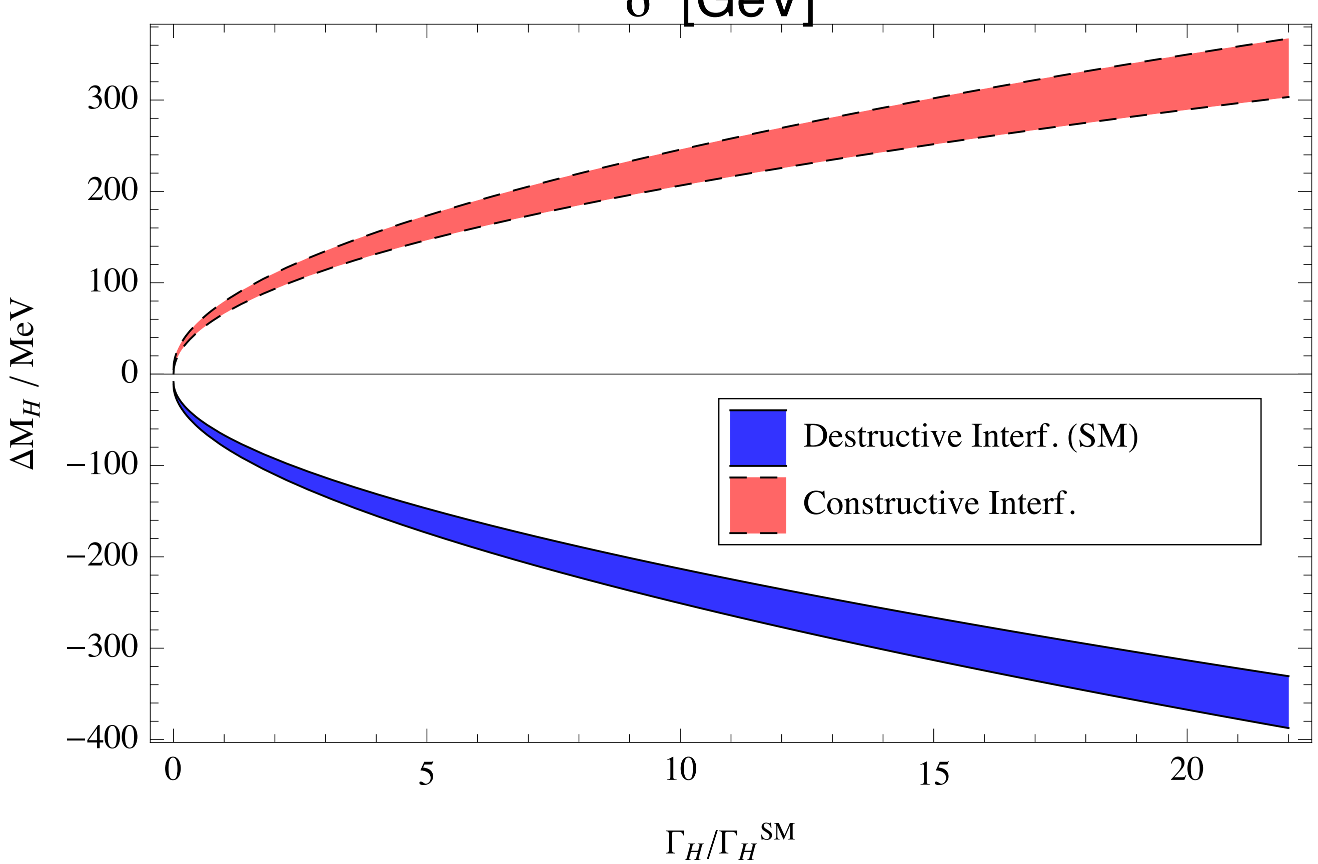
# A big *thank you* to all contributors!

A. Ballestrero, C. Becot, F. Bernlochner, H. Brun, A. Calandri, F. Campanario, F. Cerutti, D. de Florian, R. Di Nardo, L. Fayard, N. Fidanza, N. Greiner, A. V. Gritsan, G. Heinrich, B. Hespel, S. Höche, F. Krauss, Y. Li, S. Liebler, E. Maina, B. Mansoulié, C. O'Brien, S. Pozzorini, M. Rauch, J. Roskes, U. Sarica, M. Schulze, F. Siegert, P. Vanlaer, E. Vryonidou, G. Weiglein, M. Xiao, S. Yue

# H→γγ: interference and mass shift

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



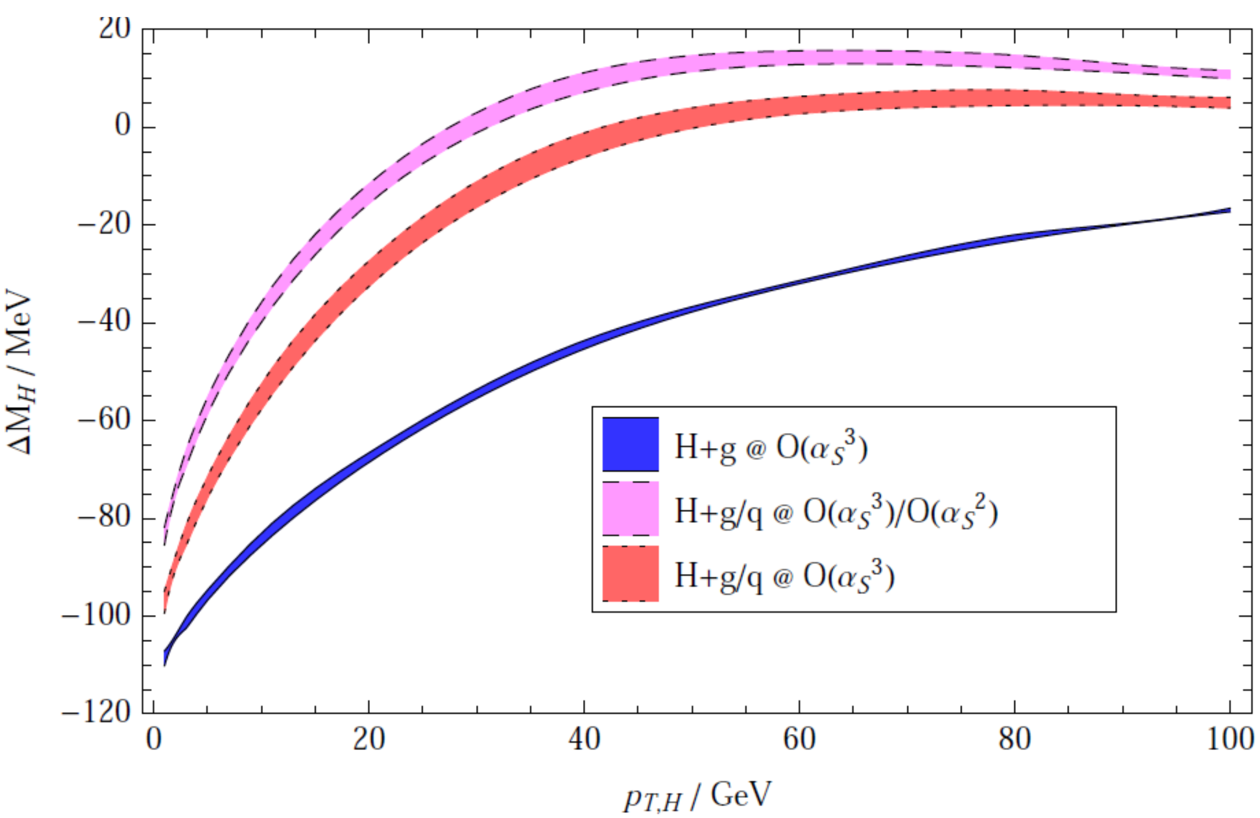



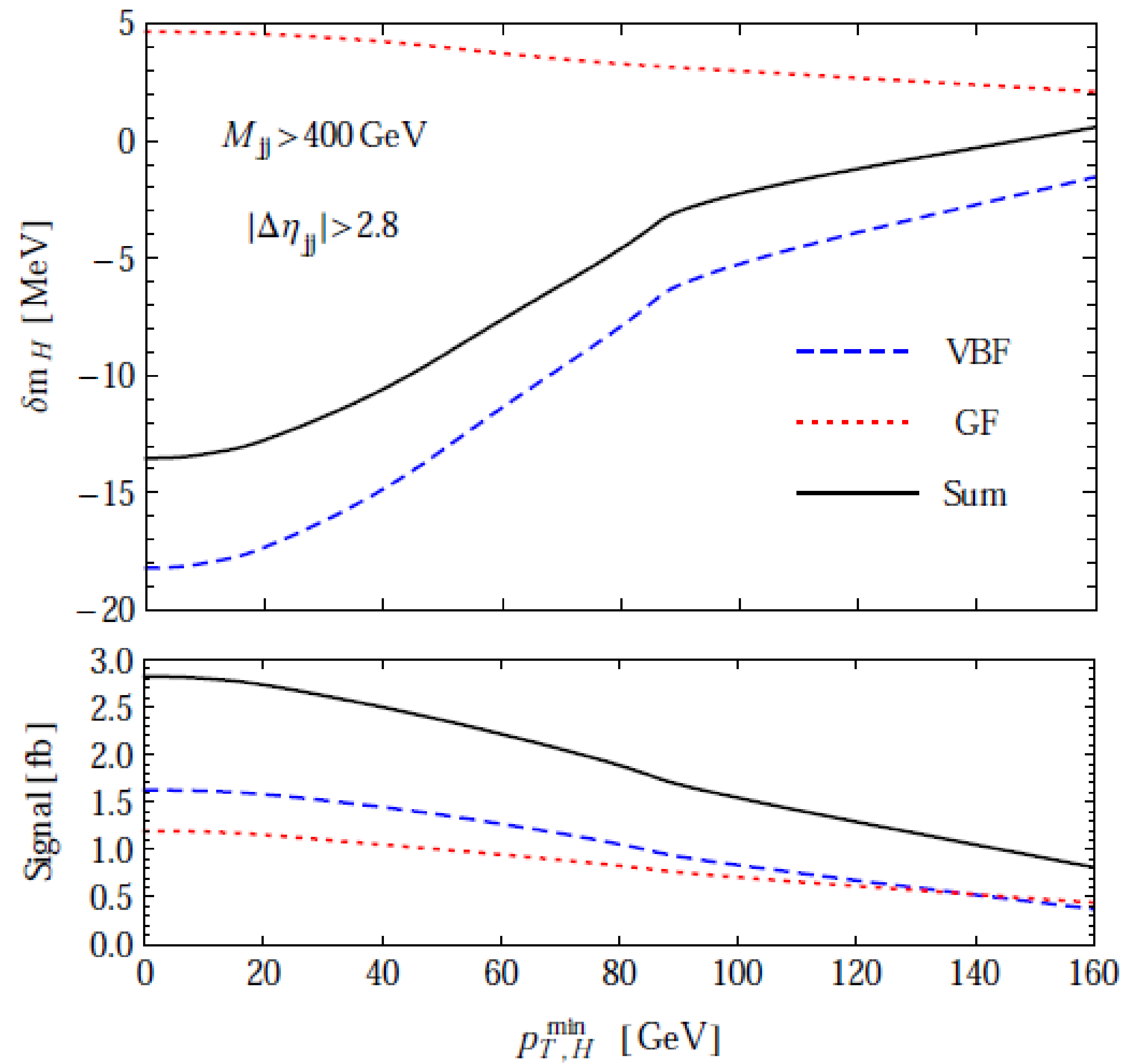

- Real part of signal gg → H → γγ and continuum gg → γγ production leads to *distortion in $m_{\gamma\gamma}$ shape*
- Peak shift ~ *independent* on the Higgs width, dependent on *environmental parameters* (detector resolution) and *interference strength*, ~ $g_i\, g_f$
- Combined with signal yield $\sigma \sim g_i^2\, g_f^2 / \Gamma_H$, can give *constraints on the Higgs width*
- Largely model-independent
- Small effect (~50 MeV, see Yanyan talk for thorough estimates)
- Need to minimize systematic uncertainties

# Using γγ as control sample

[Martin (2012); Dixon and Li; de Florian et al (2013), Coradeschi et al (2015)]

- Mass shift *strongly sensitive* on selection cuts → can use γγ both as signal and as control regions, reduce systematic error w.r.t. e.g. ZZ
- Largest mass shift at low $p_t$ → 2-bin analysis
- Particularly useful: γγ + 2j samples: opposite effect in GF and VBF, very small mass shift
- Good control region: $m_{jj}$ > 400 GeV, standard photon cuts (small shift, non negligible rates)

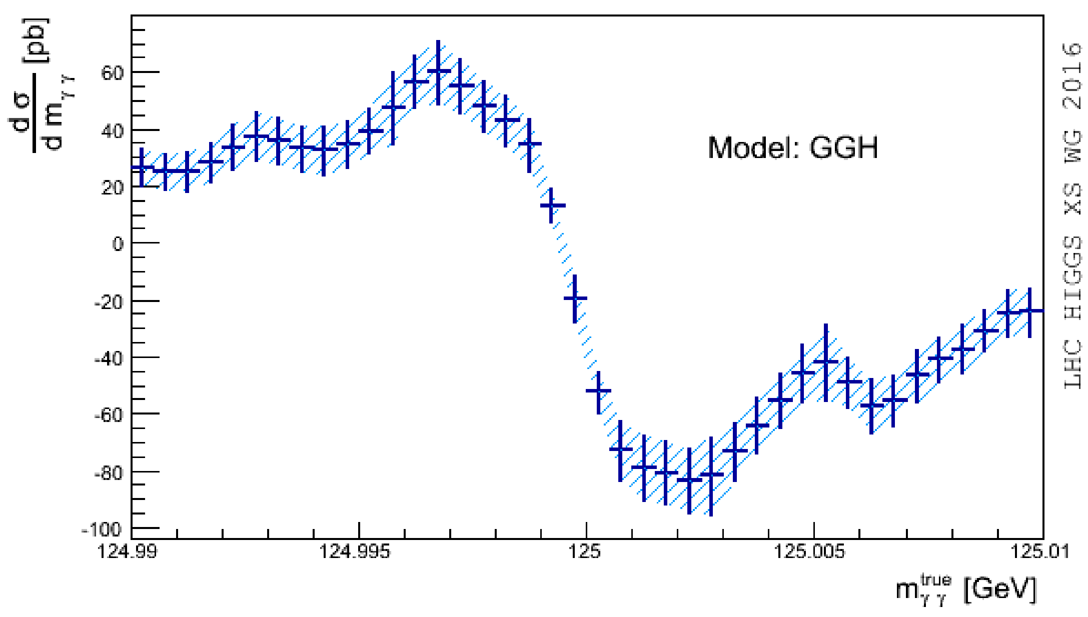


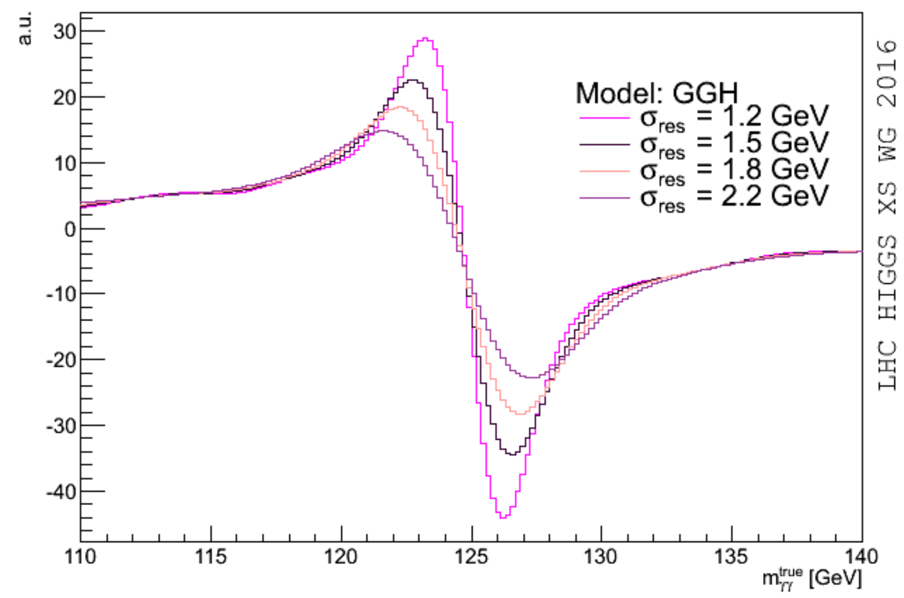
# Available tools and K-factors

- Parton shower implementation available, Sherpa+DIRE (Höche et al.)

Interference




Interference, w. energy smearing

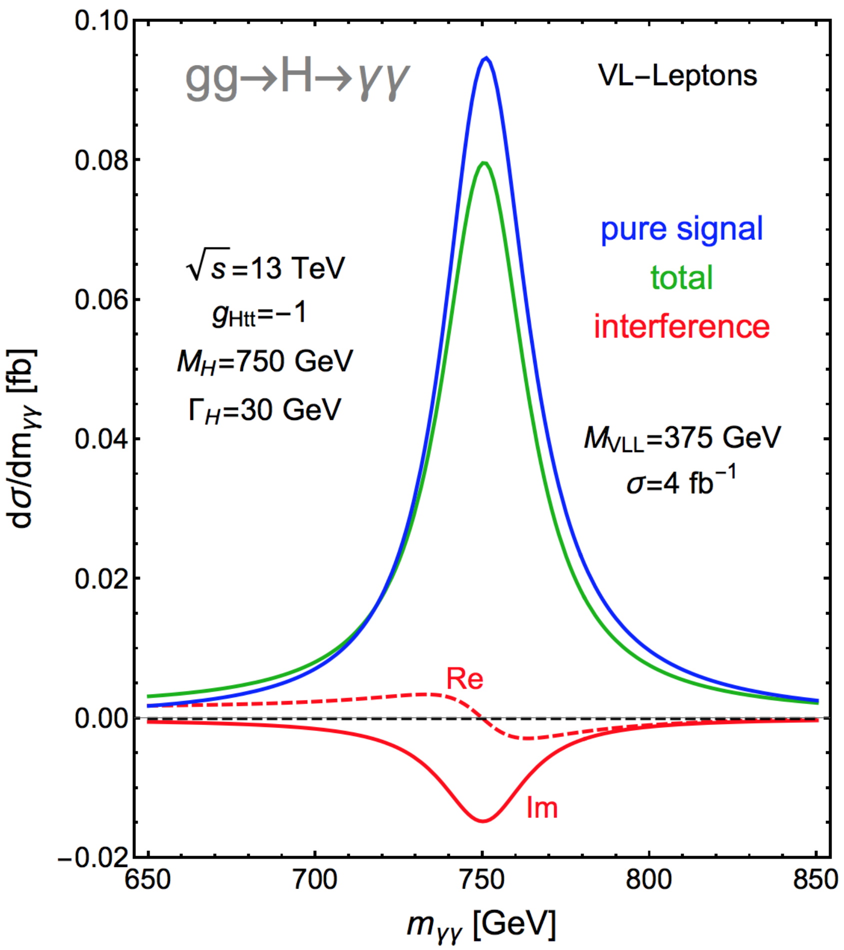


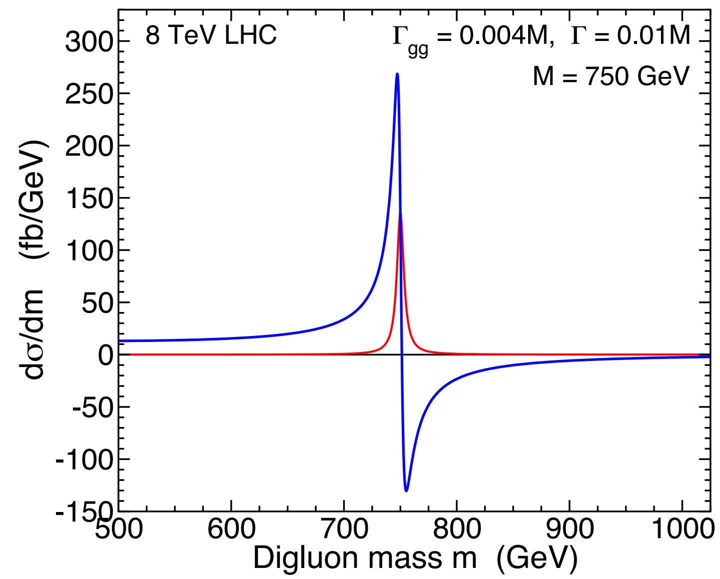

- ATLAS analysis: → see Yanyan's talk
- Signal: NNLO. Background/interference: NLO
- NNLO background: 3-loop, mass effects…
- Reasonable assumption: $K_B \in [1, K_S]$. Motivated by NLO K-factor

# Interference for BSM resonances

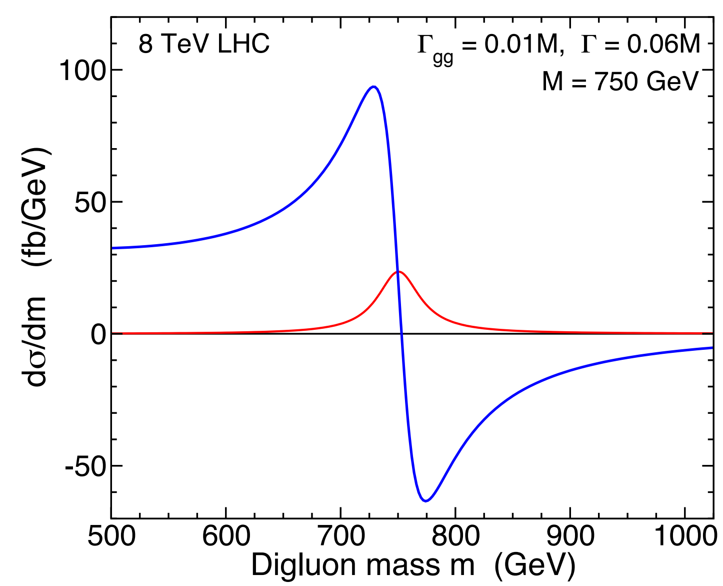
[Djouadi et al; Hespel et al; Dawson, Lewis; Martin (2016)]

Photons

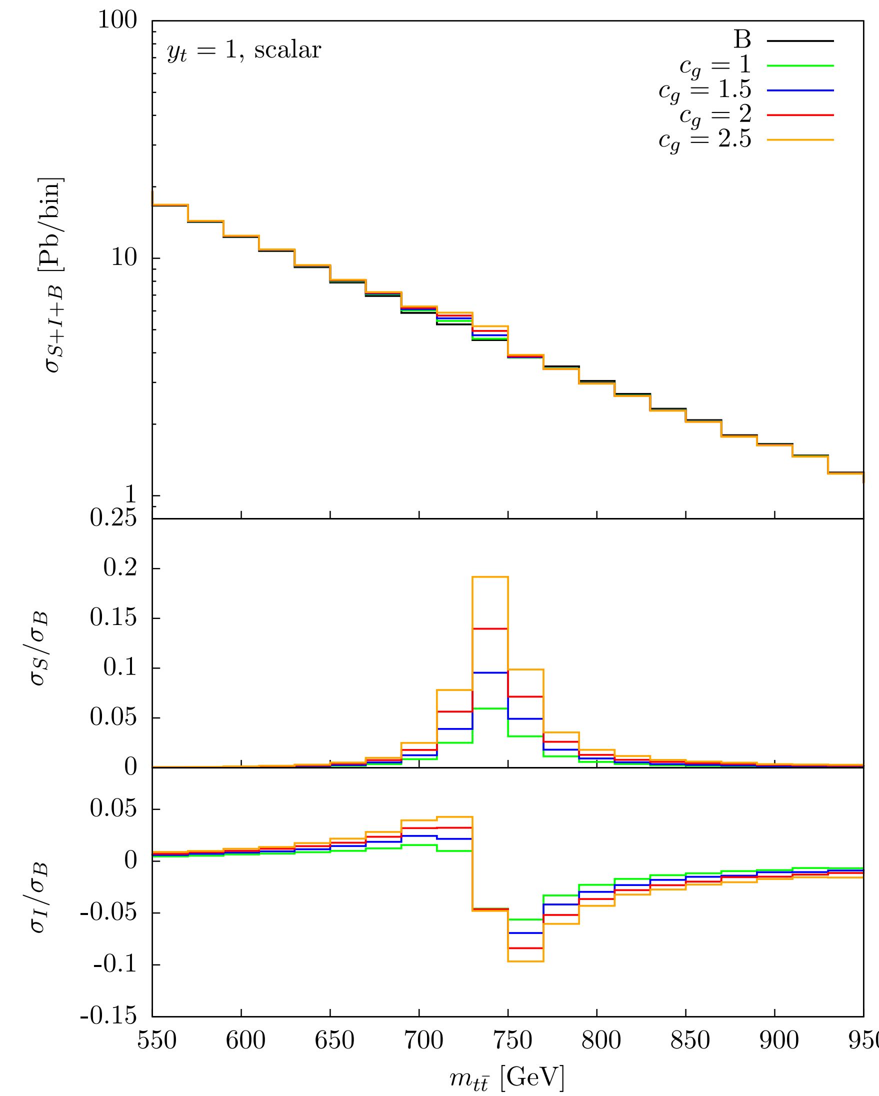



gluons




Tops

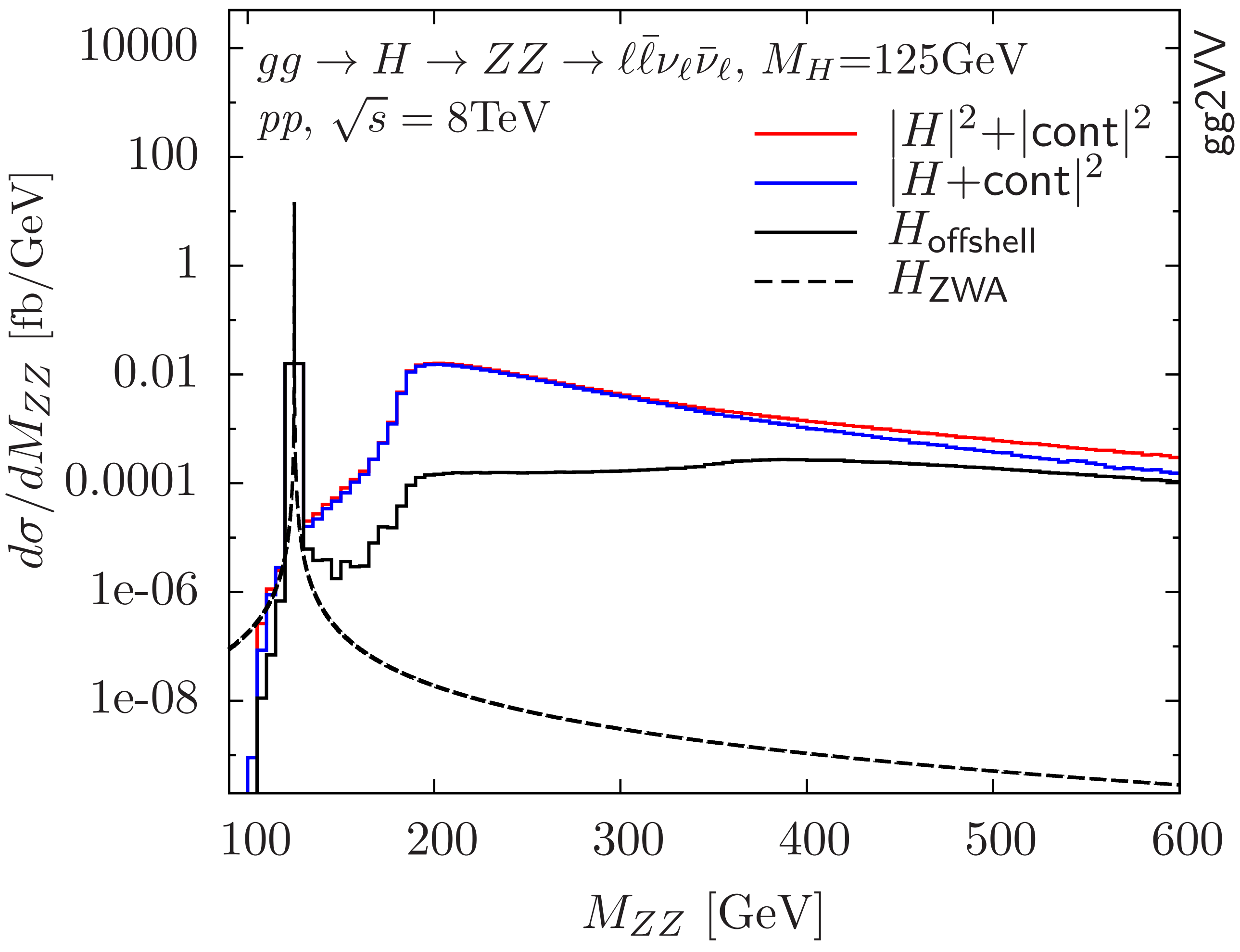


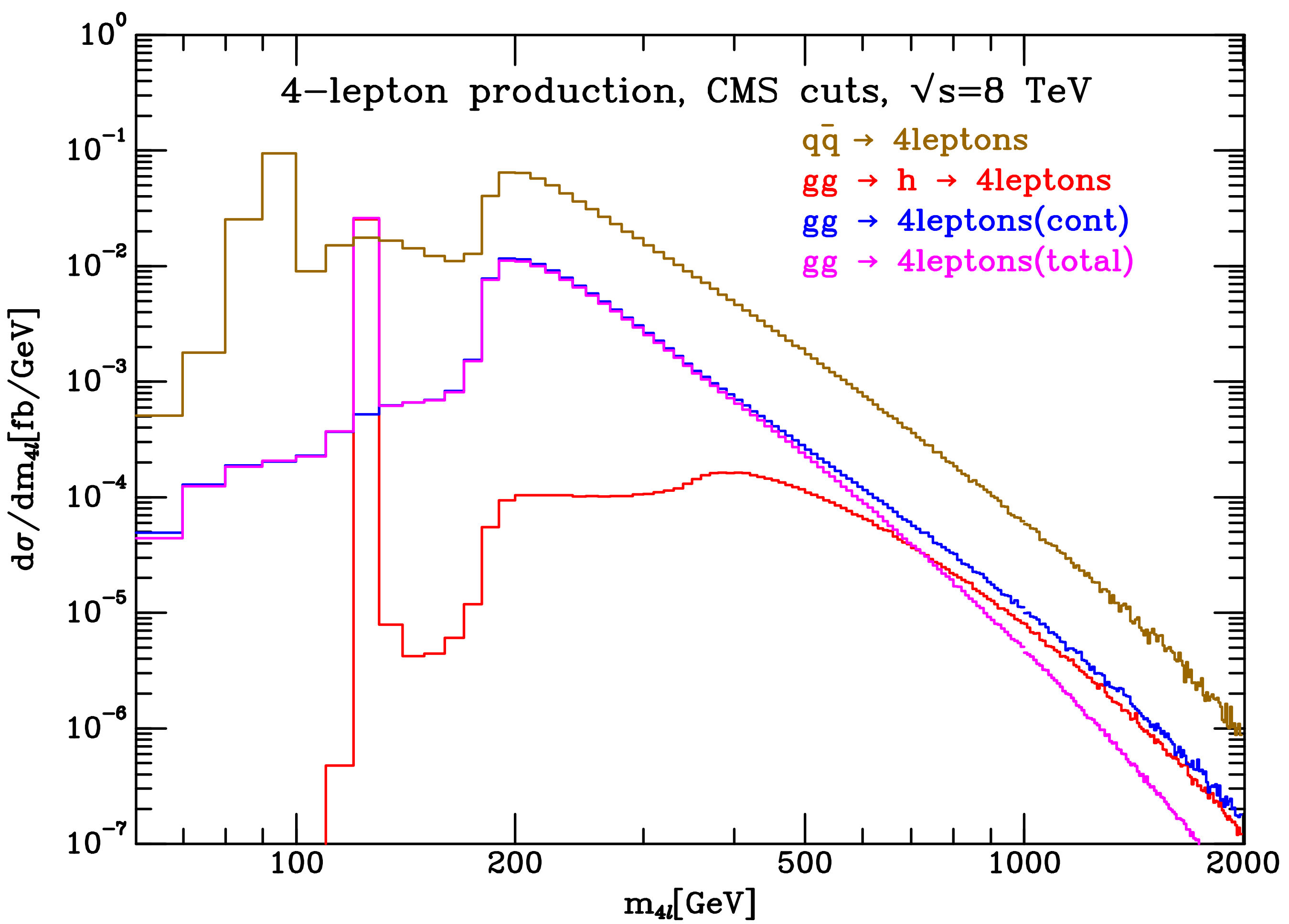

- Interference effects likely to play a role for (high mass) resonances
- Same spirit, but situation can be *qualitatively different* (top, thresholds…)
- Cannot just rescale Higgs results

# Off-shell Higgs

[NK, Passarino (2012); FC, Melnikov (2013); Campbell, Ellis, Williams (2013)]

- Despite being a *narrow resonance*, in the SM the Higgs develops a sizable *high invariant mass tail* (enhanced decay to real longitudinal W/Z)
- The tail is *width independent* → direct extraction of off-shell couplings
- Under assumptions on on/off-shell coupling correlations → strong bounds on Higgs width by combining off-shell tail and signal yield



# Relevance for $\sigma_{tot}$ and available tools

At the inclusive level, $\sigma_{off}$ ~ 10% enhancement of BW result. *However*

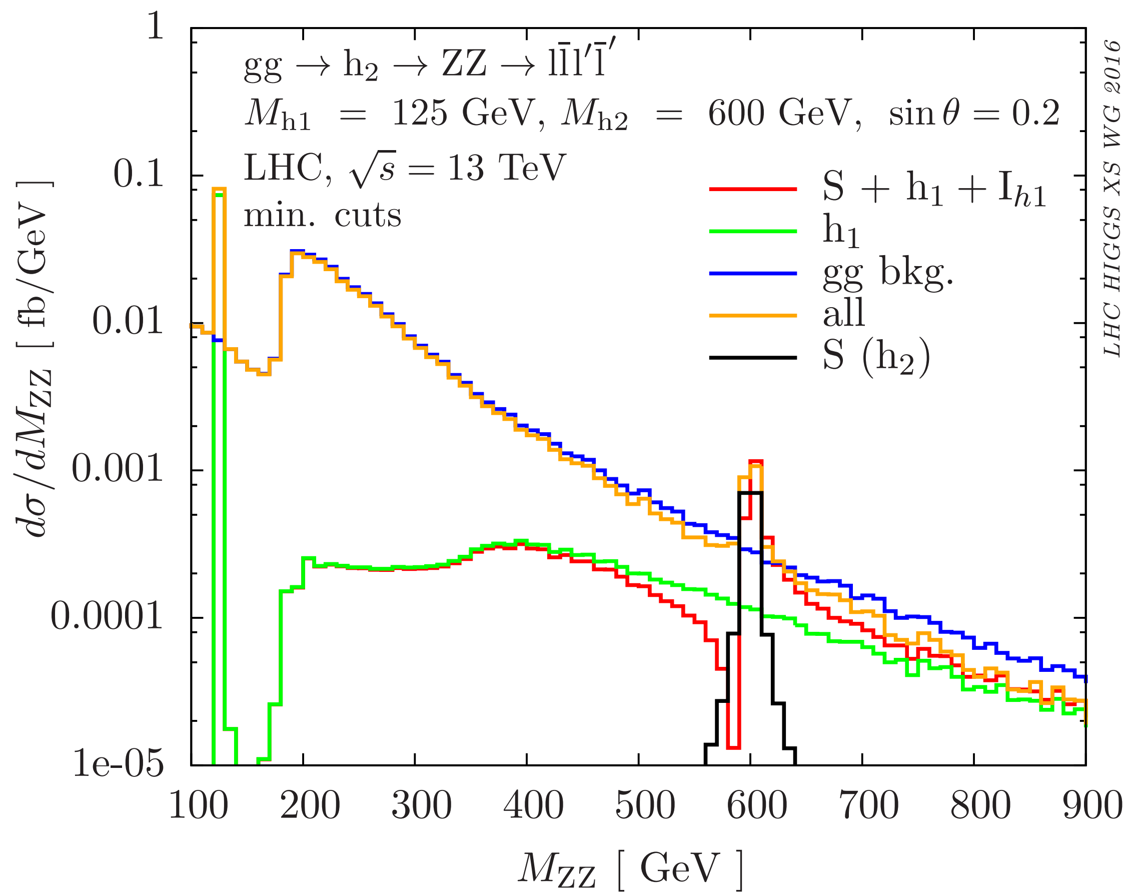
- Off-shell effects completely killed by $m_{4l}$ cuts for ZZ analysis
- WW analysis require a $m_T$ cut to avoid large off-shell contamination

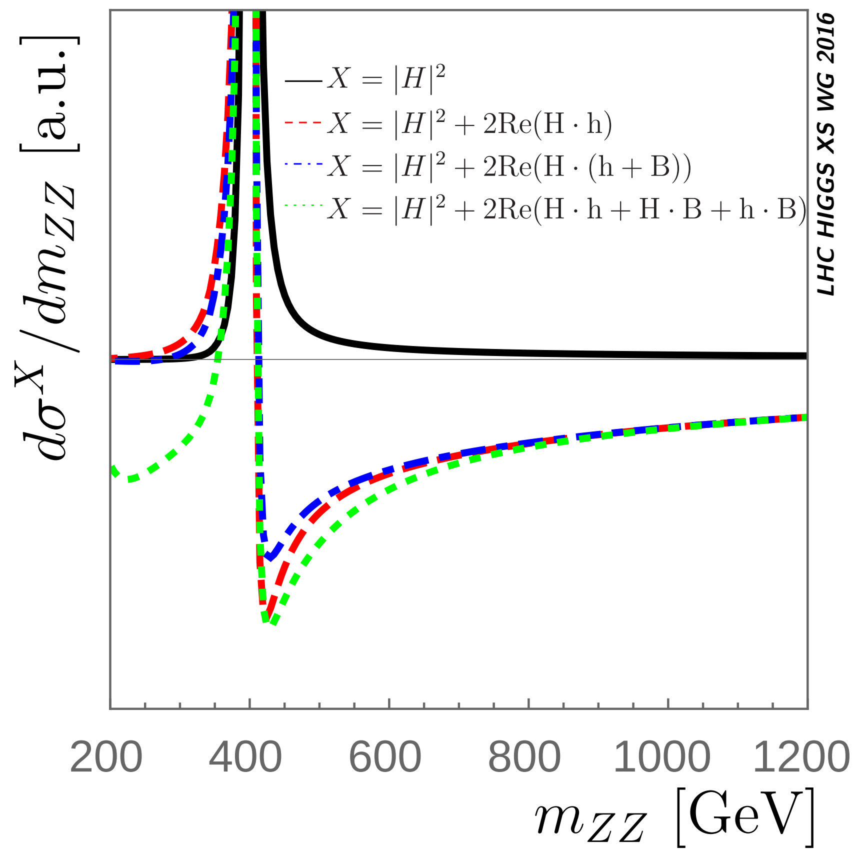
Status of theoretical predictions

- Many available tools for LO background and interference: gg2VV, MCFM, MadGraph5_aMC@NLO, OpenLoops+Sherpa, GoSam, JHUGen/MELA+MCFM… Benchmark results in YR4
- Signal: NNLO. Benchmark K-factors in the off-shell region in YR4
- Background/interference: LO/LO+PS (→see Yanyan)/Merged LO+PS
- After YR4: first exact results for NLO background/interference in the intermediate off-shell region $m_{4l}$ < 350 GeV

# Studies for benchmark BSM models

## Singlet extension

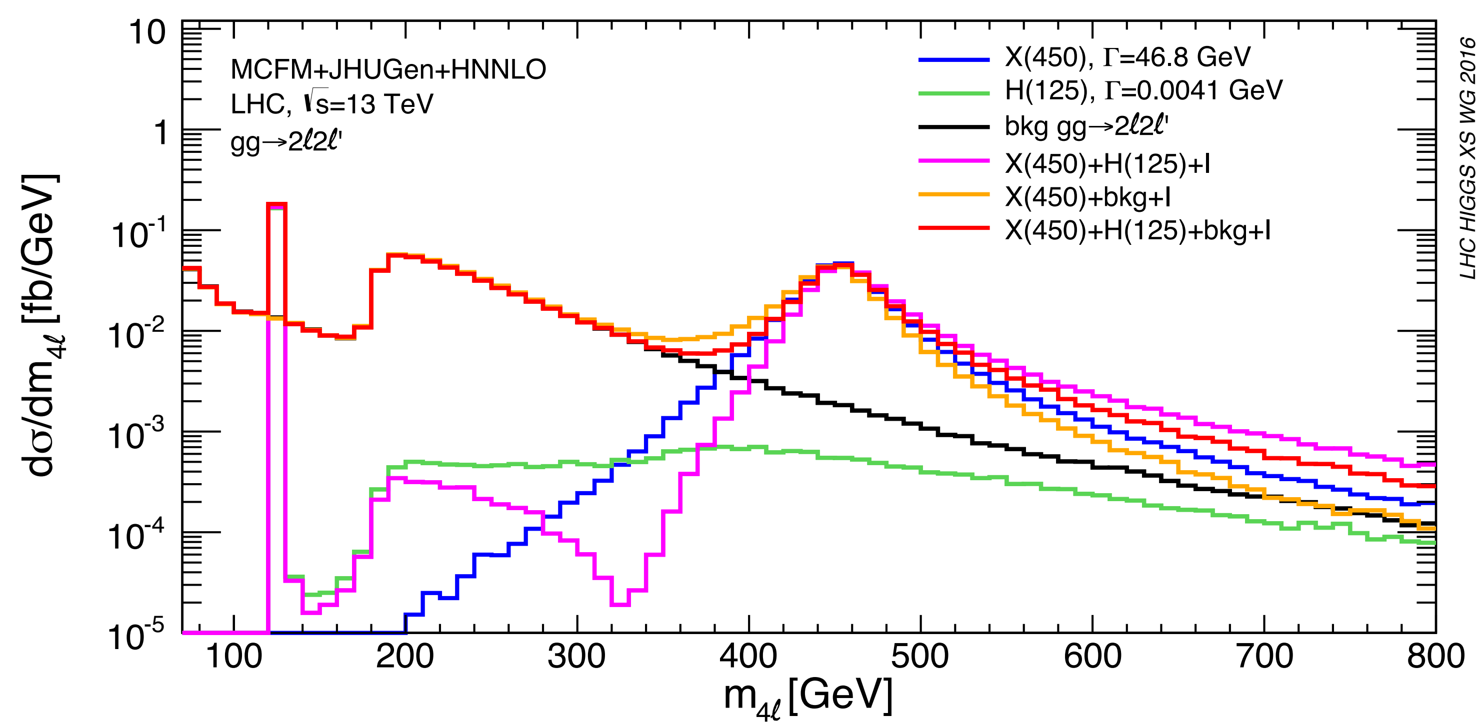



2HDM

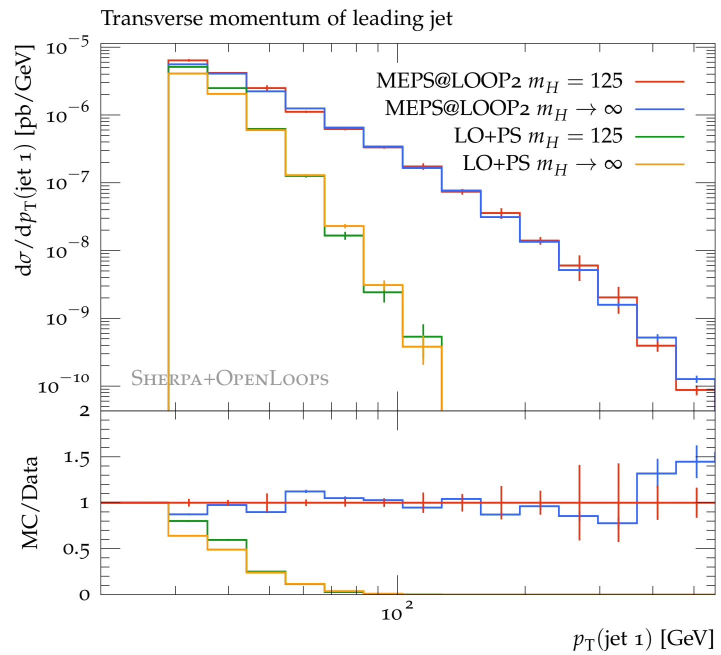
## Generic couplings

- Non trivial interference patterns
- Signal/background interference
- Light/heavy interference



# Beyond LO

## PS merging: gg→(H)→WW [OpenLoops+Sherpa]

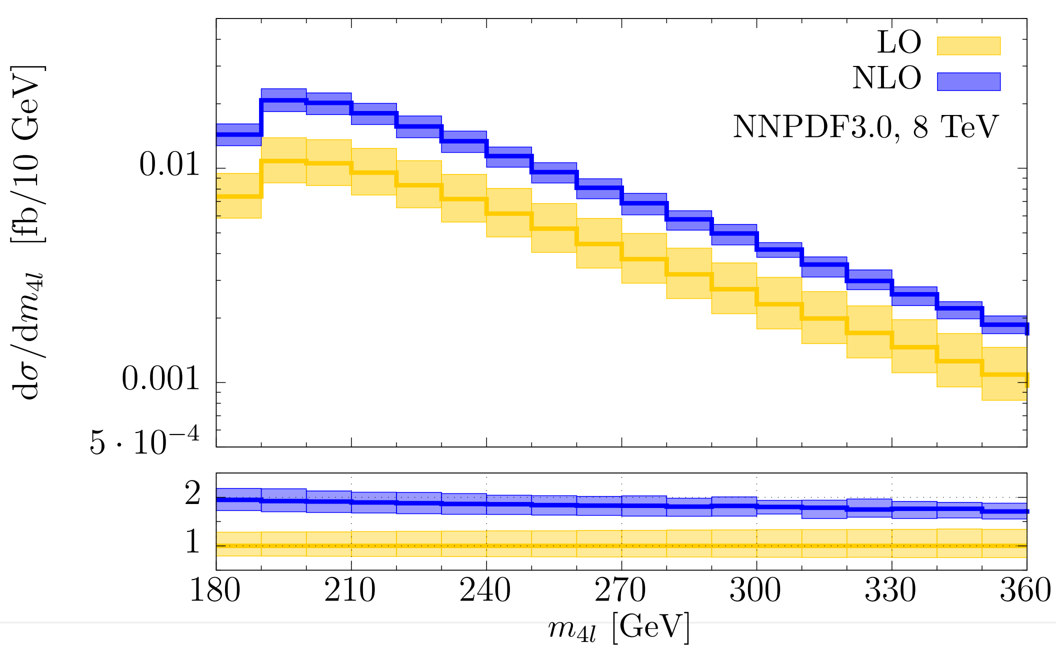



Results as expected

- Harder $p_t$ spectrum
- More jet activity

## NLO for the background, $m_{4l}$ ~ 2 $m_V$

[FC, Melnikov, Röntsch, Tancredi (2015)]



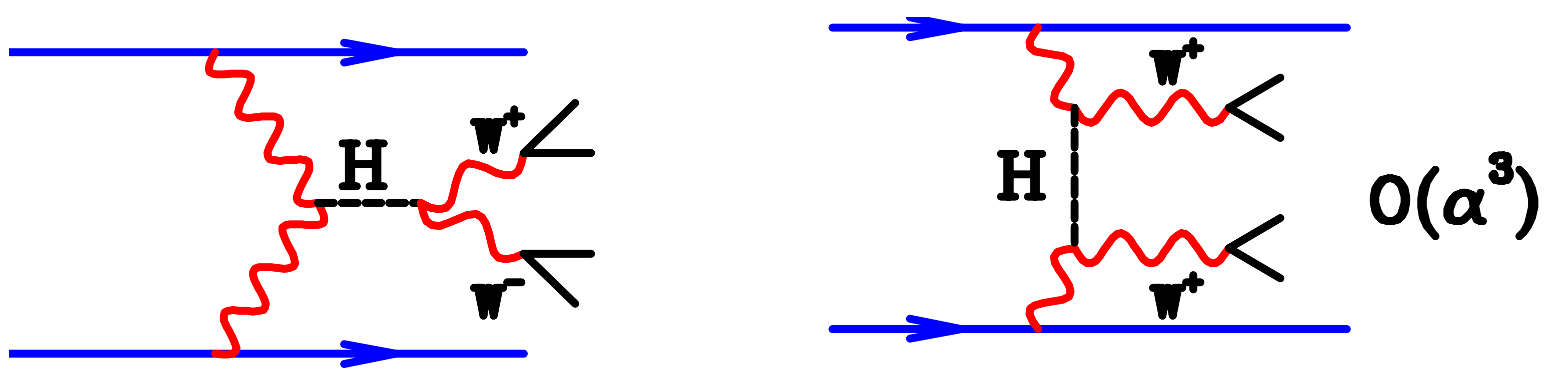

No surprises

- K-factor ~ Higgs
- K-factor rather flat

# An alternative approach: VBF

[Campbell, Ellis (2015)]

- No K-factor problem
- Theory systematics (interpretation issues…) somewhat different
- Complementary approach w.r.t. ggF




- Smaller rates → less significance. Rough estimate: at the end of Run II similar bound to ggF now (but different theory systematics)
- Dedicated generators available (e.g. VBFNLO, MCFM, PHANTOM, JHUGen/MELA, MadGraph5_aMC@NLO…)

# Precision predictions for $gg\ (\to H) \to VV$ signal-background interference

Signal: $gg \to H$ cross section at NLO QCD with finite $t$ and $b$ mass effects (important for off-shell Higgs with $M_{VV} \gtrsim 2M_t$: 5–10% correction) (scale uncertainty: 10–15%) Djouadi, Spira, Zerwas, Graudenz (1991-1995); N$^3$LO in soft expansion with $M_t \to \infty$ (scale uncertainty $\approx 3\%$) C. Anastasiou, C. Duhr, F. Dulat, F. Herzog, B. Mistlberger arXiv:1503.06056; NLO EW corrections important for off-shell Higgs (8% at $M_{VV} \sim 500$ GeV) A. Bredenstein, A. Denner, S. Dittmaier, M. Weber arXiv:hep-ph/0604011 (also arXiv:1111.6395)

Background: $pp \to ZZ$ and $pp \to WW$ at NNLO QCD with massless quarks (scale uncertainty $\approx 3\%$), F. Cascioli, T. Gehrmann, M. Grazzini, S. Kallweit, P. Maierhofer, A. von Manteuffel, S. Pozzorini, D. Rathlev, L. Tancredi, E. Weihs arXiv:1405.2219 and T. Gehrmann, M. Grazzini, S. Kallweit, P. Maierhofer, A. von Manteuffel, S. Pozzorini, D. Rathlev, L. Tancredi arXiv:1408.5243

$gg \to VV$ enters $pp \to VV$ at $\mathcal{O}(\alpha_s^2\alpha^2)$ (NNLO QCD correction to $pp \to VV$) with $\sim$ 20–25% (LO!) scale uncertainty; $\mathcal{O}(\alpha_s^3\alpha^2)$: unknown $gg \to VV$ NLO QCD $K$-factor, but expected to be similar to signal ($\sim 1.6$); confirmed by $gg \to ZZ$ NLO QCD calculation in massless quark approximation (see next page)

11–17% (9–12%) NNLO QCD correction to $pp \to ZZ$ ($WW$) for $\sqrt{s} = 7$–14 TeV

$gg \to VV$ contributes to full NNLO correction to $pp \to ZZ$ ($WW$) with 60% (35%)

$\to$ NLO QCD correction to $gg \to VV$ is of similar size or larger than residual scale uncertainty of $pp \to VV$ at NNLO QCD $\Rightarrow$ calculation is important and by a similar argument the calculation of the NLO QCD correction to signal-background interference

# Precision predictions for $gg\ (\to H) \to VV$ signal-background interference

Work towards $gg\ (\to H) \to VV$ signal-background interference and $gg \to VV$ continuum background beyond leading order, i.e. beyond $\mathcal{O}(\alpha_s^2)$:

NLO and NNLO calculation for $gg\ (\to H) \to WW \to \ell\nu\ell\nu$ interference with $M_H = 600$ GeV in soft-gluon approximation (very good accuracy for inclusive signal cross section)
M. Bonvini, F. Caola, S. Forte, K. Melnikov, G. Ridolfi arXiv:1304.3053
$\to$ interference $K$-factors are generally very similar to signal $K$-factors (also for kinematic distributions)

Soft gluon resummation to all orders for $gg\ (\to H) \to ZZ \to \ell\ell\ell'\ell'$ interference, $100$ GeV $< M_{ZZ} < 1000$ GeV, effects signal like C. Li, H. Li, D. Shao, J. Wang arXiv:1504.02388

Technical bottleneck for unapproximated $gg \to VV$ calc. at NLO: two-loop virtual corrections

Two-loop $gg \to VV \to 4$ leptons amplitudes with massless quarks calculated by two groups:
F. Caola, J. Henn, K. Melnikov, A. Smirnov, V. Smirnov arXiv:1503.08759
A. v. Manteuffel, L. Tancredi arXiv:1503.08835

Calculation of NLO $gg \to ZZ$ cross section in model where $Z$ bosons only couple to $t$ quarks in $s/M_t^2$ expansion (LO) yields K-factor of $1.5$–$2$ for $180$ GeV $< M_{ZZ} < 340$ GeV
(LO QCD comparison with exact $M_t$: $M_t \to \infty$ poor for $M_{ZZ} \gtrsim 300$ GeV)
K. Melnikov, M. Dowling arXiv:1503.01274

Calculation of NLO $gg \to ZZ$ $(WW)$ cross section in massless quark approximation yields K-factor of $1.5$–$2$ ($1.2$–$1.8$, jet veto!) F. Caola, K. Melnikov, R. Röntsch, L. Tancredi arXiv:1509.06734 (arXiv:1511.08617), $gg \to WW$: no $t$–$b$ loop graphs $\to$ $\mathcal{O}(10\%)$ missing

# Precision predictions for $gg\ (\to H) \to VV$ signal-background interference

2-loop calculation with full top mass dependence beyond
current capabilities for continuum background amplitude

Approximate using method of *expansion by regions* V.A. Smirnov et al.:
Large Mass Expansion (LME): expand in $s/m_t^2$,
formally valid for $s < m_t^2$, but extrapolation to $s \gg m_t^2$ feasible with reasonable accuracy (1605.01380: $10\% - 20\%$)

$gg \to ZZ$: first-order expansion by Dowling, Melnikov (1503.01274), suppressed Vec. $t\bar{t}Z$ coupling is missing

$gg \to ZZ$: recent, complementary extensions to high orders ($\sim 6$) in $s/m_t^2$:

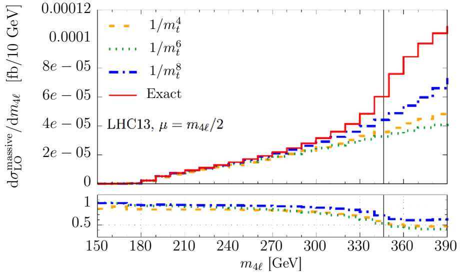
J. Campbell, K. Ellis, M. Czakon, S. Kirchner arXiv:1605.01380
on-shell $Z$'s: $M_{ZZ} > 2M_Z$, extrapolation to $s \gg m_t^2$

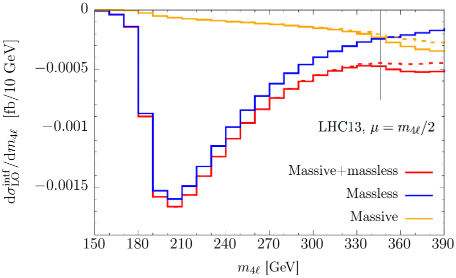
F. Caola, M. Dowling, K. Melnikov, R. Röntsch, L. Tancredi arXiv:1605.04610
off-shell $Z$'s including leptonic decays for $s \lesssim (2m_t)^2$

# Precision predictions for $gg\ (\to H) \to VV$ signal-background interference

F. Caola, M. Dowling, K. Melnikov, R. Röntsch, L. Tancredi

LO 4-lepton invariant mass distribution (massive: LME vs. exact),
left: background only, right: interference

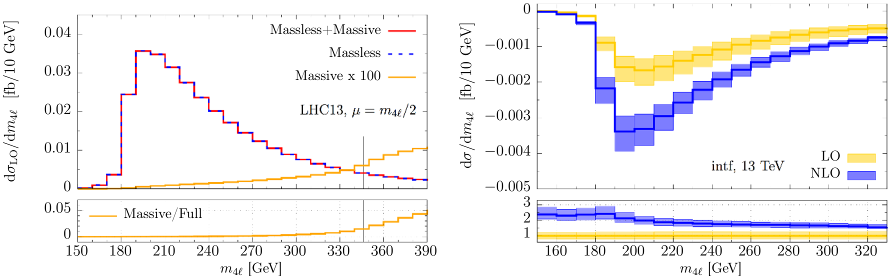


# Precision predictions for $gg\ (\to H) \to VV$ signal-background interference

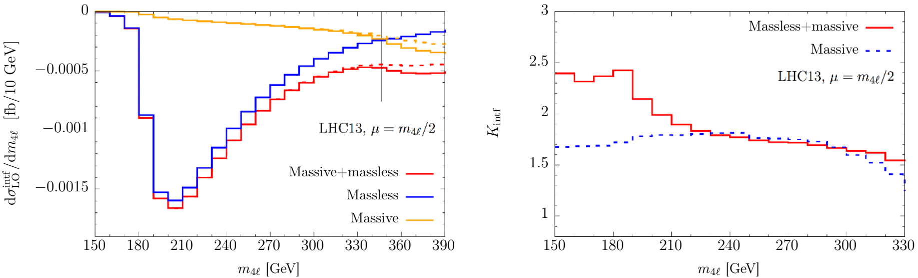
F. Caola, M. Dowling, K. Melnikov, R. Röntsch, L. Tancredi

4-lepton invariant mass distributions, left: background only (LO), right: interference with factor-2 scale variation (lower panel: $K$-factor)



# Precision predictions for $gg\ (\to H) \to VV$ signal-background interference

F. Caola, M. Dowling, K. Melnikov, R. Röntsch, L. Tancredi




$m_{4\ell} \sim 2m_t$: $K_{\text{signal}} \approx K_{\text{bkg}} \approx K_{\text{intf}}$

$m_{4\ell} \sim 2M_Z$: $K_{\text{intf}}$ different from $K_{\text{signal}}$ and $K_{\text{bkg}}$

$K_{\text{intf}} \approx \sqrt{K_{\text{signal}} K_{\text{bkg}}}$ for full considered $m_{4\ell}$ range

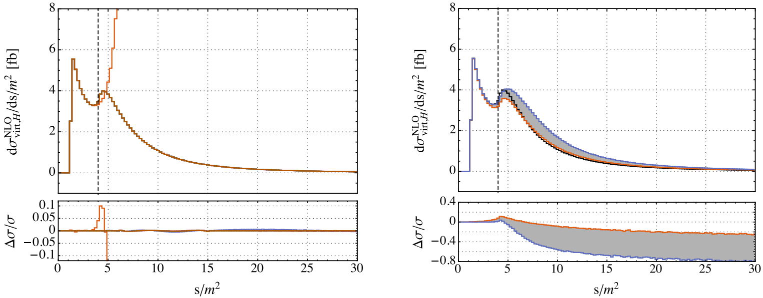
# Precision predictions for $gg\ (\to H) \to VV$ signal-background interference

J. Campbell, K. Ellis, M. Czakon, S. Kirchner

Improving naive LME with

1. Conformal Mapping, Padé approximants (superior, selected)
2. Rescaling with exact LO result

Test with $H$ signal: Comparison (improved) LME vs. exact for virtual NLO corrections: left: 1., right: 2.

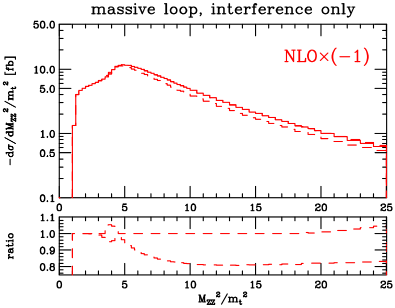



similar behaviour found when comparing for LO $gg \to ZZ$ continuum

# Precision predictions for $gg\ (\rightarrow H) \rightarrow VV$ signal-background interference

J. Campbell, K. Ellis, M. Czakon, S. Kirchner

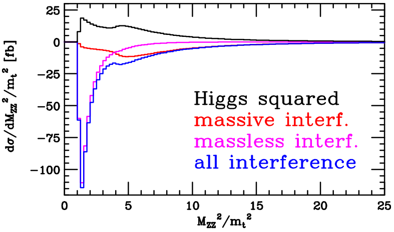
Uncertainty on NLO interference due to improved LME ($\lesssim 20\%$ on approximated part):

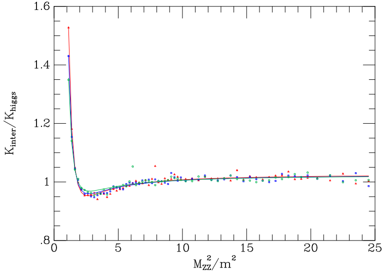


# Precision predictions for $gg\ (\to H) \to VV$ signal-background interference

J. Campbell, K. Ellis, M. Czakon, S. Kirchner

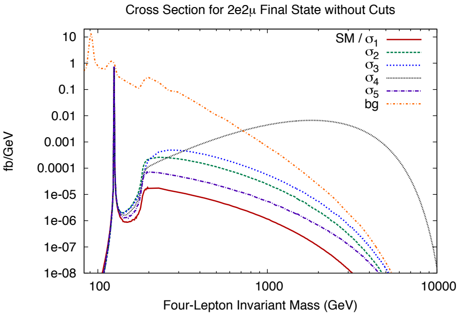
Full prediction and ratio of $K$-factors for interference and signal:



# High-mass $H \to VV$ signal and BSM constraints

Constraining higher dimensional operators with the off-shell Higgs (see below)
Disentangling New Physics with the off-shell Higgs boson
EFT studies including the off-shell Higgs boson




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

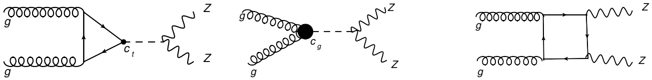
$\mathcal{O}_5 = \frac{2}{v} H Z_\mu \partial^2 Z^\mu$  J. Gainer, J. Lykken, K. Matchev, S. Mrenna, M. Park arXiv:1403.4951

Also: modification of lepton angular distributions $\longrightarrow$ good control with 300 fb$^{-1}$ I. Anderson et al. arXiv:1309.4819

# 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))

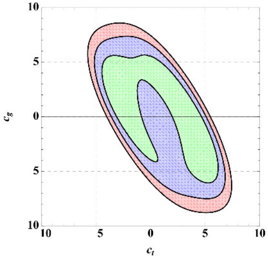



$$\mathcal{L} = -c_t \frac{m_t}{v} \bar{t}th + \frac{g_s^2}{48\pi^2} c_g \frac{h}{v} G_{\mu\nu}G^{\mu\nu}$$

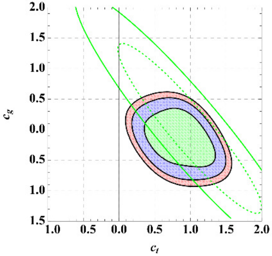
$$\mathcal{M}_{gg\to ZZ} = \mathcal{M}_h + \mathcal{M}_{bkg} = c_t \mathcal{M}_{c_t} + c_g \mathcal{M}_{c_g} + \mathcal{M}_{bkg}$$

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

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

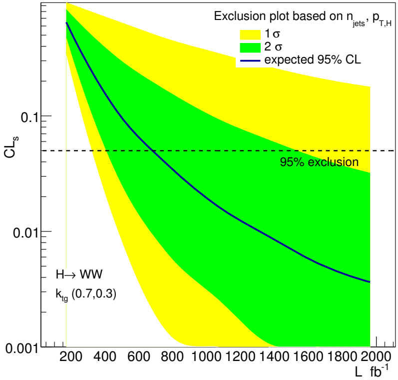


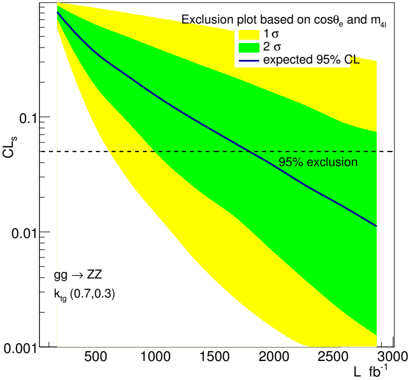

LHC 8 TeV CMS data




LHC 14 TeV 3 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)

# Summary

- YR4 Off-shell and interference chapter has been finalised
  (51 pages with SM and BSM benchmark results and studies,
  and recommendations)
- Subgroup has provided regular updates on new developments
  (active field, rapid progress)
- Future tools goal: High-mass NLO $gg \to VV$ (exact?) merged with PS
  $\to$ public event generator for experimental studies
- Not much discussion in WG about BSM/EFT constraints, despite
  research activity/interest
- Proposal: additional Theory convener with BSM focus (EFT expertise)