Higgs off-shell and interference studies

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Off-shell Interpretations Task Force of the LHC Higgs Working Group

https://twiki.cern.ch/twiki/bin/view/LHCPhysics/HiggsOffshellTaskForce

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Fermilab (online)

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Overview

- Off-shell Higgs width bounds: recap and status
- LHC Higgs WG Off-Shell Task Force: models, EFTs, interpretations
- Recent developments: off-shell Higgs couplings in $H^* \to ZZ \to \ell\ell\nu\nu$
- Recent developments: precision tools
- Recent developments:
  2-loop $gg \to ZZ$ amplitude with full top mass effects
- Higgs interference effects at the one-loop level (1HSM)
- Conclusions

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: $\Gamma_H < 1.1$ GeV, 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 $\left(\Gamma_H = \mathcal{O}(\Gamma_{H,SM})\right)$ 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 V. Barger, M. Ishida, W. Keung (2012); K. Cheung, J. Lee, P. Tseng (2013); J. Ellis, T. You (2013); A. Djouadi, G. Moreau (2013); P. Bechtle, S. Heinemeyer, O. Stal, T. Stefaniak, G. Weiglein (2014)
- $e^+e^- \rightarrow Z(H \rightarrow \text{all})$: construct recoil mass and measure HZZ coupling $\rightarrow \Gamma_H$ can be determined indirectly, ILC: 6%–11% accuracy M. Peskin (2013), T. Han et al. (2013)
- Direct threshold scan at muon collider: Γ_H accuracy 4%–9% T. Han, Z. Liu (2013)
- Higgs width determination could provide first evidence for BSM Higgs interactions

Off-shell Higgs Width Bounds Recap: The Method

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

F. Caola, K. Melnikov arXiv:1307.4935

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

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 $g_i \to \xi\, g_i,\quad g_f \to \xi\, g_f,\quad \Gamma_H \to \xi^4\, \Gamma_H$

see L. Dixon, Y. Li arXiv:1305.3854

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

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: $\sigma_{\text{off-peak}}/\sigma_{\text{on-peak}} \propto \Gamma_H$

competitive constraints on Higgs width feasible with LHC data (but assumption)

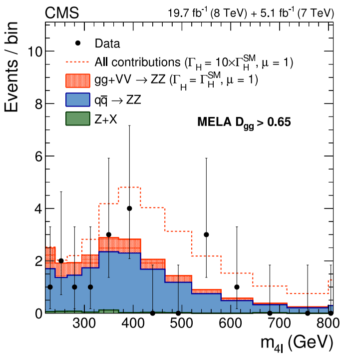
large interference with cont. background (necessary to prevent unitarity violation) weakens bounds

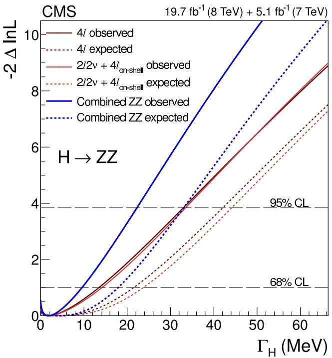
First CMS Analysis

arXiv:1405.3455

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





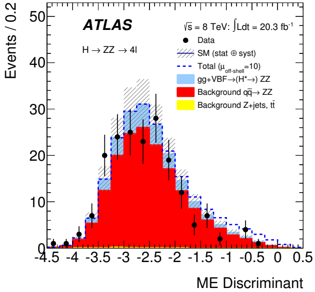
$\Gamma_H < 5.4\ \Gamma_H^{SM}$ (95% CL)

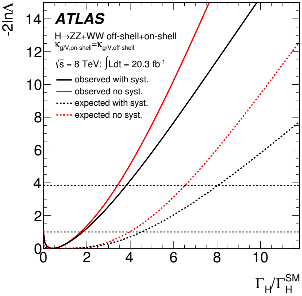
First ATLAS Analysis

arXiv:1503.01060

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 95%-CL upper limit $[5.1, 8.6]$ ($[6.7, 11]$ expected)





$$\Gamma_H < [4.5, 7.5]\ \Gamma_H^{SM}\ (95\%\ \text{CL})$$

Off-shell Higgs Width: Summary and Current Bounds

- Direct Higgs width measurement at LHC limited by mass resolution: $\Gamma_H < 600\ \Gamma_H^{SM}$
- $H \to ZZ, WW$ in ggF & VBF @ LHC: $\mathcal{O}(10\%)$ off-shell high-mass Higgs signal contribution with large Higgs(-Higgs)-continuum interference provides complementary physics information (similar at high-energy linear collider)
- high-mass Higgs tail not Higgs width dependent $\longrightarrow$ provides complementary constraints on Higgs couplings and Higgs width Γ_H (when combined with on-peak data)
- Assuming no E-dependence of relevant Higgs couplings, a bound on Γ_H can be obtained; optimise bound with fully differential discriminant (Matrix Element Method)
- LHC Run 2: improved bounds, high-mass $H \to VV$ EFT and BSM benchmark studies

- ATLAS latest: arXiv:1808.01191 $\Gamma_H < 14.4\text{MeV} \to \Gamma_H < 3.5\ \Gamma_H^{SM}$ (95%CL) for 36fb^{-1} at 13TeV
- CMS latest: arXiv:1901.00174 $\Gamma_H = 3.2^{+2.8}_{-2.2}\text{MeV}$ (68%CL), $\Gamma_H < 9.16\text{MeV} \to \Gamma_H < 2.2\ \Gamma_H^{SM}$ (95%CL) for 80fb^{-1} at 13TeV and 20 & $5\,\text{fb}^{-1}$ at 8 & 7 TeV, respectively
- no updates with full Run-2 data published yet

Off-shell Task Force

Models, EFTs, Interpretations: Guidelines

- discuss and make recommendations on which models/AnomCoupls/EFTs should be investigated with what priority in the context of off-shell $gg \to H \to VV$ analyses
- carefully consider and compare theoretical assumptions/choices made
- explore to what degree compatibility/translatability between ATLAS and CMS results is feasible

Aleksandr Azatov, Adam Falkowski, Andrei Gritsan, Christophe Grojean, NK, Ennio Salvioni, Eleni Vryonidou

See also:

- Offshell & Interference Meeting (25 November 2019) [link]
- HXSWG Offshell Interpretations 1st Joint Meeting (10 March 2020) [link]
- HXSWG Offshell Interpretations 2nd Joint Meeting (16 April 2020) [link]
- HXSWG Offshell Interpretations 3rd Joint Meeting (8 July 2020) [link]
- HXSWG Offshell Interpretations 4th Joint Meeting (23 September 2020) [link]

Models, EFTs, Interpretations: Discussion Points

- EFT effects in $gg\ (\to H) \to ZZ$
- Relation between the Higgs and Warsaw bases
- What types of BSM benchmark models should be analysed? Light degrees of freedom up to what scale? In particular to uncover limitations of EFT fits. Are common models sufficient (MSSM, 2HDM, SM+scalar)? What toy models (composite inspired, ...)?
- Interplay with other channels due to shared couplings, e.g. top production. How to disentangle coefficients? Independent subsets? Proper treatment? Best use of limited number of degrees of freedom in fits. How to expand? Take into account (better) bounds on relevant Wilson coefficients obtained in other channels.
- Can off-shell data resolve on-shell parameter degeneracy?
- Statistics/data analysis methods available to include BSM effects in backgrounds (relative to Higgs production) when determining bounds on Wilson coefficients/model parameters?
- and others, see TWiki page [link]

Models, EFTs, Interpretations: Road Map

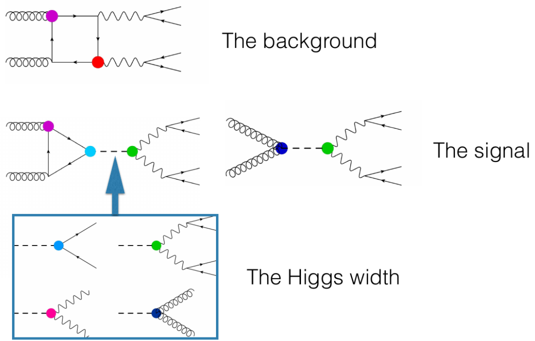
1. Immediate issues:
   - discuss and converge to a "minimal" list of couplings/operators that deserve priority at this stage
   - clarify basis issues and make recommendations
   - take into account bounds on relevant Wilson coefficients obtained in other channels
2. Medium-term issues:
   - what types of BSM benchmark models should be analysed? Light degrees of freedom up to what scale? In particular to uncover limitations of EFT fits.
   - interplay with other channels due to shared couplings, e.g. top production. How to disentangle operators? Proper general treatment? Independent subsets?
   - take into account VBF $\rightarrow$ H $\rightarrow$ VV (VBF/VH)
3. Long-term issues:
   - take into account SMEFT effects in background amplitudes
   - take into account NLO effects in EFT studies
   - study specific BSM extended with higher-dimensional operators

SMEFT analysis of $gg \to H \to VV \to$ leptons

Extension of the SM by dimension-6 operators Q_i composed of SM fields, which are invariant under the SM gauge symmetries (C_i: Wilson coefficients):

$$\mathcal{L}_{\mathrm{SMEFT}} = \mathcal{L}_{\mathrm{SM}} + \sum_i C_i Q_i$$

detailed Higgs basis definition $\to$ Adam Falkowski's write-up for task force



graphs by Eleni Vryonidou

What can $gg \to ZZ$ including off-shell tell us about the SMEFT?

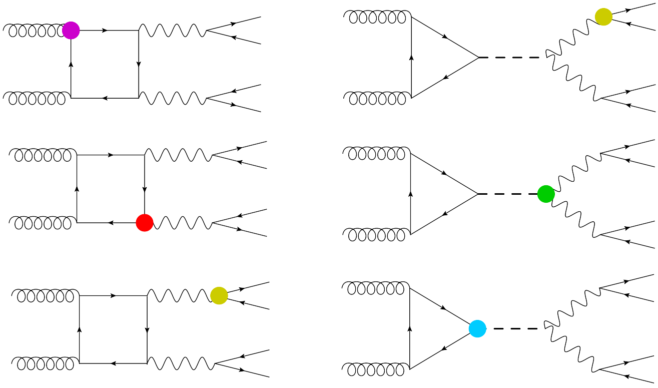
$\to$ Ennio Salvioni et al.'s write-up for task force

Models, EFTs, Interpretations: write-up's for task force

- Adam Falkowski (finalised):
  Summary of the Higgs basis parametrization of the SMEFT
- Alex Azatov, Christophe Grojean, Ennio Salvioni, Jorge de Blas (finalised):
  What can off-shell Higgs measurements tell us about BSM physics?
  (use off-shell observables to lift universal flat directions of on-shell Higgs rates, when giving up coupling universality: off-shell can have leading resolving power in certain scenarios)
- Eleni Vryonidou (draft):
  Off-shell Higgs production in the SMEFT
  (studies using SMEFT@NLO implementation of SMEFT operators with MG5_aMC@NLO)

Off-shell Higgs production in the SMEFT

Sample Feynman diagrams for off-shell Higgs production and corresponding background with EFT insertions:

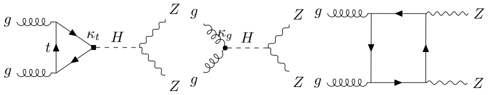


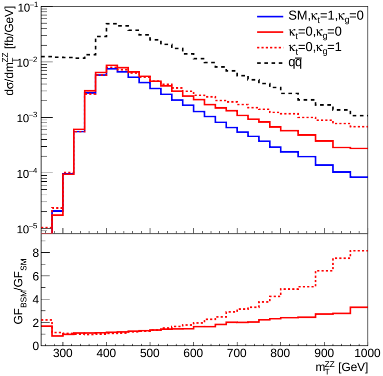
graphs by Eleni Vryonidou

Recent Developments: Phenomenology

Off-shell Higgs couplings in $H^* \to ZZ \to \ell\ell\nu\nu$

Dorival Gonçalves, Tao Han, Sze Ching Iris Leung, Han Qin arXiv:2012.05272





Study of off-shell Higgs boson measurement in $pp \to H^* \to Z(\ell^+\ell^-)Z(\nu\bar{\nu})$ at the HL-LHC. New Physics sensitivity is parametrised in terms of the Higgs boson width, effective field theory framework and a non-local Higgs-top coupling form factor. Significant sensitivities found for the studied NP scenarios when the transverse ZZ mass and machine-learning techniques are exploited.

Recent Developments: Precision Tools

Off-shell Higgs effects:

Four lepton production in gluon fusion: Off-shell Higgs effects in NLO QCD

Massimiliano Grazzini, Stefan Kallweit, Marius Wiesemann, Jeong Yeon Yook
arXiv:2102.08344

Parton shower matching:

Four-lepton production in gluon fusion at NLO matched to parton showers

Simone Alioli, Silvia Ravasio, Jonas Lindert, Raoul Röntsch arXiv:2102.07783

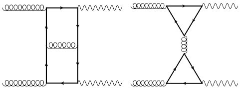
W^+W^- production at NNLO+PS with MiNNLO$_{\mathrm{PS}}$

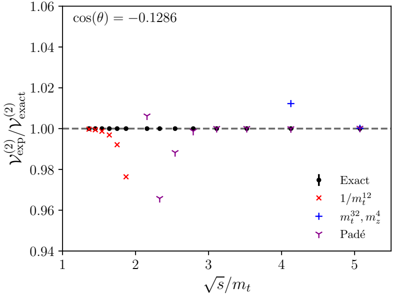
Daniele Lombardi, Marius Wiesemann, Giulia Zanderighi arXiv:2103.12077

Recent Developments: Loop Amplitudes: Top Mass Effects

Two-loop helicity amplitudes for gg $\rightarrow$ ZZ with full top-quark mass effects

Bakul Agarwal, Stephen Jones, Andreas von Manteuffel arXiv:2011.15113





Sample graphs and comparison of the $\sqrt{s}$ dependence of the unpolarised interference $\mathcal{V}^{(2)}$ with expansion for large and small top-quark mass.

Higgs interference effects at the one-loop level

NK, Alexander Lind, Philipp Maierhöfer, Weimin Song arXiv:1905.03296

with contributions from Silvan Kuttimalai

1-Higgs Singlet Model (1HSM) benchmark points:

$M_{h_1} = 125$ GeV and $\mu_1 = \lambda_1 = \lambda_2 = 0$

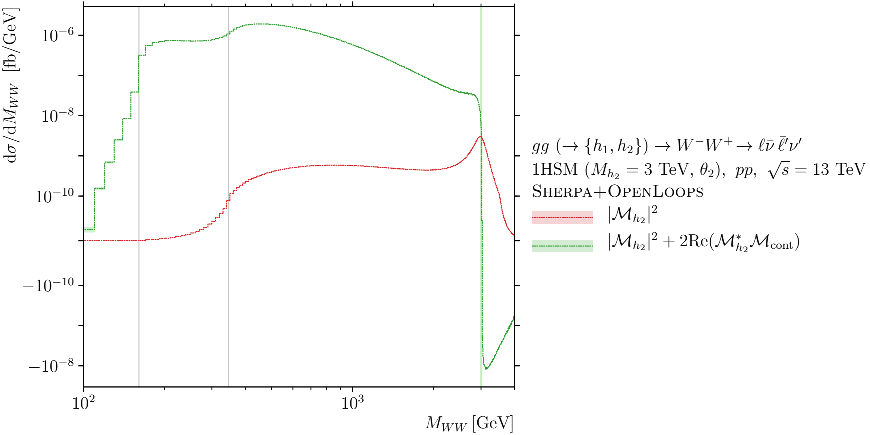
M_{h_2} [GeV]	700	1000	1500	3000
θ_1	$\pi/15$	$\pi/15$	$\pi/22$	$\pi/45$
	≈ 0.21	≈ 0.21	≈ 0.14	≈ 0.07
θ_2	$\pi/8$	$\pi/8$	$\pi/12$	$\pi/24$
	≈ 0.39	≈ 0.39	≈ 0.26	≈ 0.13

θ_1 compatible with current experimental limits

θ_2 for comparison, to illustrate mixing angle dependence

Motivation

Heavy Higgs hunting: “bump” vs. interference



$$|\mathcal{M}_{h_1} + \mathcal{M}_{h_2} + \mathcal{M}_{\mathrm{cont}}|^2 = \underbrace{|\mathcal{M}_{h_2}|^2}_{\text{“bump”}} + \underbrace{2\mathrm{Re}(\mathcal{M}^*_{h_2}\mathcal{M}_{\mathrm{cont}})}_{\text{interference}} + \dots$$

Higgs **interference** is a constituent part of the **BSM signal**

Non-trivial phase at loop level; cuts

Non-trivial phase $\longrightarrow$ loop-level amplitude contributions can substantially change interference cross sections and distributions

For example:

[Dixon, Siu] hep-ph/0302233

[NK, O'Brien, Vryonidou] arXiv:1506.01694

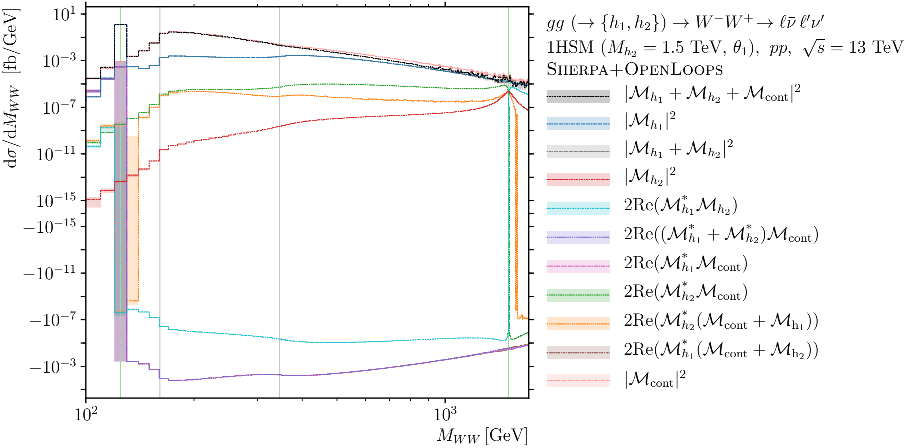
[Campbell, Carena, Harnik, Liu] arXiv:1704.08259

Applied cuts:

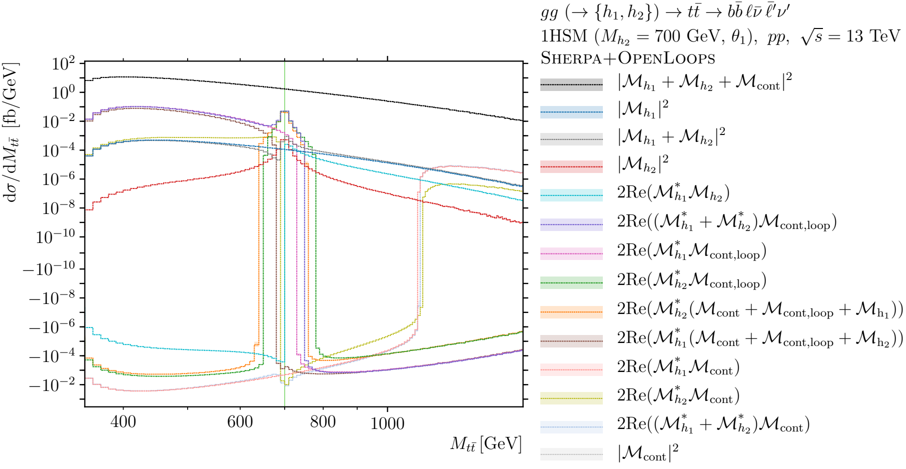
$$p_{T\ell_1} > 22\,\mathrm{GeV}, \quad p_{T\ell_2} > 15\,\mathrm{GeV}, \quad |\eta_\ell| < 2.5, \quad M_{\ell\bar{\ell}'} > 10\,\mathrm{GeV}, \quad \not{p}_T > 20\,\mathrm{GeV},$$

$$p_{Tj} > 30\,\mathrm{GeV}, \quad |\eta_j| < 4.7, \quad \Delta R_{j\ell} > 0.4$$

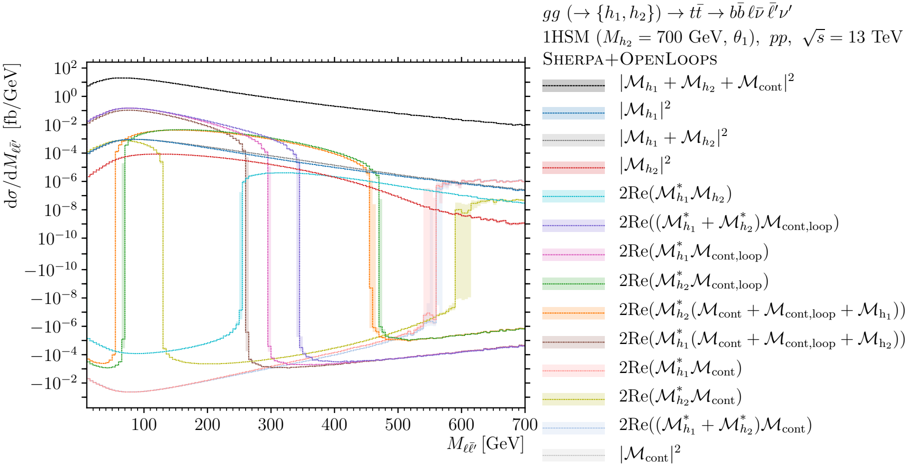
Distributions: WW



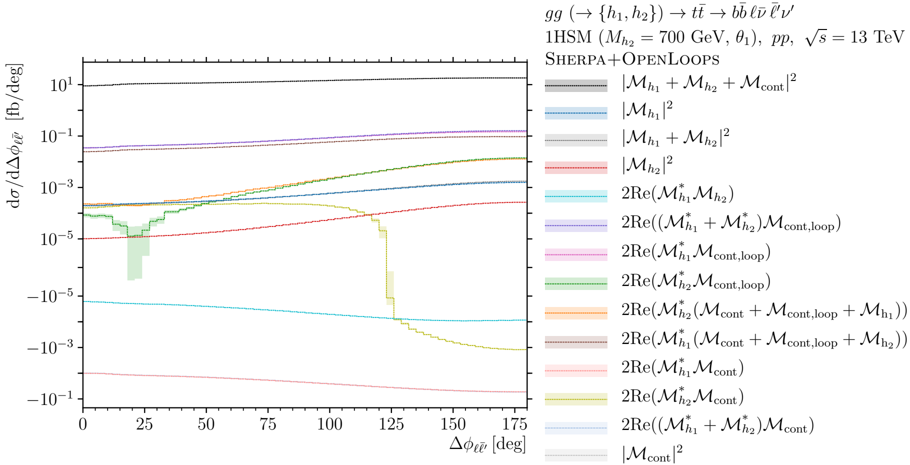
Distributions: $t\bar{t}$



Distributions: $t\bar{t}$



Distributions: $t\bar{t}$



(My) Conclusions

- Precision: impressive progress: 2-loop with full m_t dependence calculated, Tools (fully diff.) for $pp \to ZZ/WW$ @ NNLO+ & PS becoming available
- Beyond specific models/benchmarks:
  Two frameworks/paradigms to study high-mass New Physics: κ or EFT
- Tools available, SMEFT@NLO MC implement. compl./being validated
  need to coordinate tools development with experiments for max. effect
- Theory $\leftrightarrow$ Experiment: most suitable EFT bases? Accord(s)?
- Finding limits for some EFT operators/κ's using some processes/signatures with certain c_i assumptions is an excellent start, but not the end
- TH, Pheno and Exp need to work together: Theoretical aspects and how to test them experimentally needs to be discussed comprehensively and jointly to fully exploit the LHC (facilitated by working groups)
- Within experiments: official support at high level is desirable
- **Producing more/better limits is not the ultimate goal**
- **(Higgs) NP characterisation is our task – or to rule it out**
- EFT validity: need to exclude light new degrees of freedom
- Theoretical work on realisations of SM deviations continues to be important

Backup Slides

1HSM benchmark points: Higgs widths

θ	M_{h_2} [GeV]	700	1000	1500	3000
θ_1	Γ_{h_1} [GeV]	$3.910(5) \times 10^{-3}$	$3.910(5) \times 10^{-3}$	$4.004(5) \times 10^{-3}$	$4.067(5) \times 10^{-3}$
	Γ_{h_1}/M_{h_1}	$3.1283(4) \times 10^{-5}$	$3.1283(4) \times 10^{-5}$	$3.2034(4) \times 10^{-5}$	$3.2537(4) \times 10^{-5}$
	Γ_{h_2} [GeV]	10.780(3)	34.295(3)	79.52(2)	86.70(3)
	Γ_{h_2}/M_{h_2}	0.015400(4)	0.034295(3)	0.053013(7)	0.028902(9)
θ_2	Γ_{h_1} [GeV]	$3.488(5) \times 10^{-3}$	$3.488(5) \times 10^{-3}$	$3.813(5) \times 10^{-3}$	$4.017(5) \times 10^{-3}$
	Γ_{h_1}/M_{h_1}	$2.7908(4) \times 10^{-5}$	$2.7908(4) \times 10^{-5}$	$3.0506(4) \times 10^{-5}$	$3.2139(4) \times 10^{-5}$
	Γ_{h_2} [GeV]	33.903(8)	116.37(4)	273.6(2)	322.5(2)
	Γ_{h_2}/M_{h_2}	0.04843(2)	0.11637(4)	0.18240(8)	0.10751(5)