Interference effects in resonant di-Higgs production in the SM+S

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DESY & Leibniz Universität Hannover

EPS-HEP Conference
Marseille, July 9th, 2025

Based on JHEP 04 (2025) 094, 2409.06651 [hep-ph] in collaboration with
Finn Feuerstake (Lebniz Uni Hannover), Tania Robens (Boskovic Inst. Zagreb), Daniel Winterbottom (Imperial College London)

DESY.

Leibniz Universität Hannover

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Take-home messages

1. Finite-width and interference effects are relevant and need to be taken into account.

2. The SM+S features relevantinterference between resonant & non-resonant di-Higgs production.

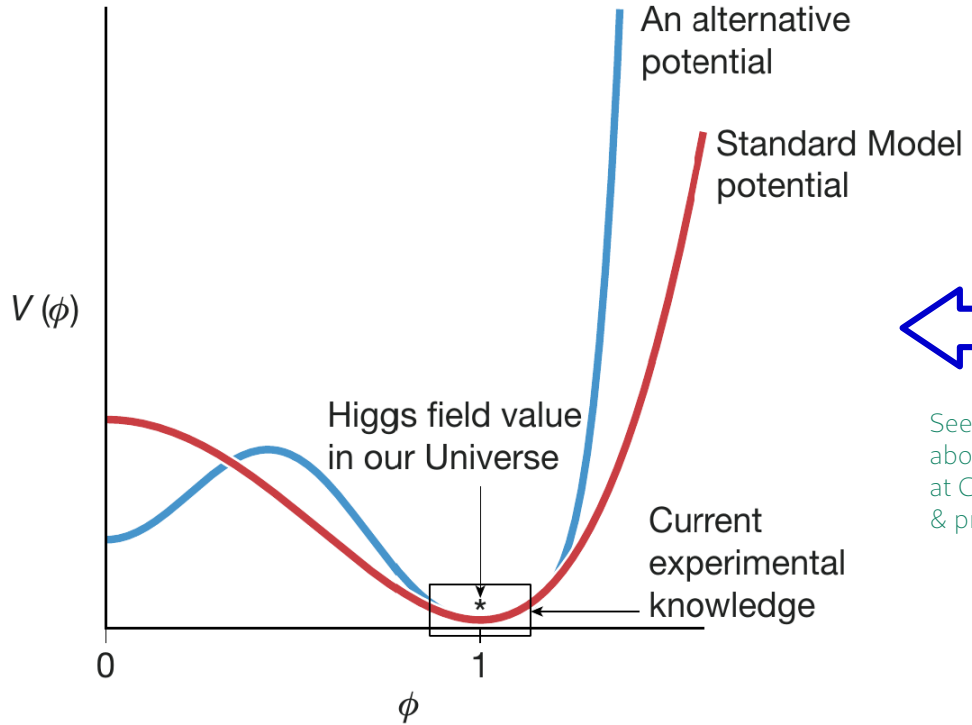
3. Beyond m_{hh}, also p_T^h and other variables are sensitive to interference.

4. We provide bounds on SM+S and characteristic benchmarks.

5. We introduce a new public tool HHReweighter to reweigh matrix elements for a fast & accurate inclusion of interference effects in various models.

Motivation I: Higgs self-coupling

G. Salam, LT. Wang, G. Zanderighi, "The Higgs turns 10", Nature 607 (2022)

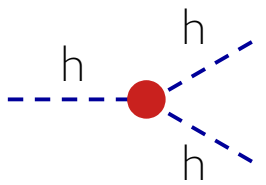


SM: minimal Higgs potential

Probe by di-Higgs production

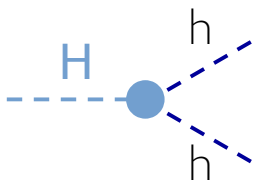
See talks on Tue/Wed about di-Higgs searches at CMS, ATLAS, HL-LHC & predictions

SM triple Higgs



λ_{hhh}

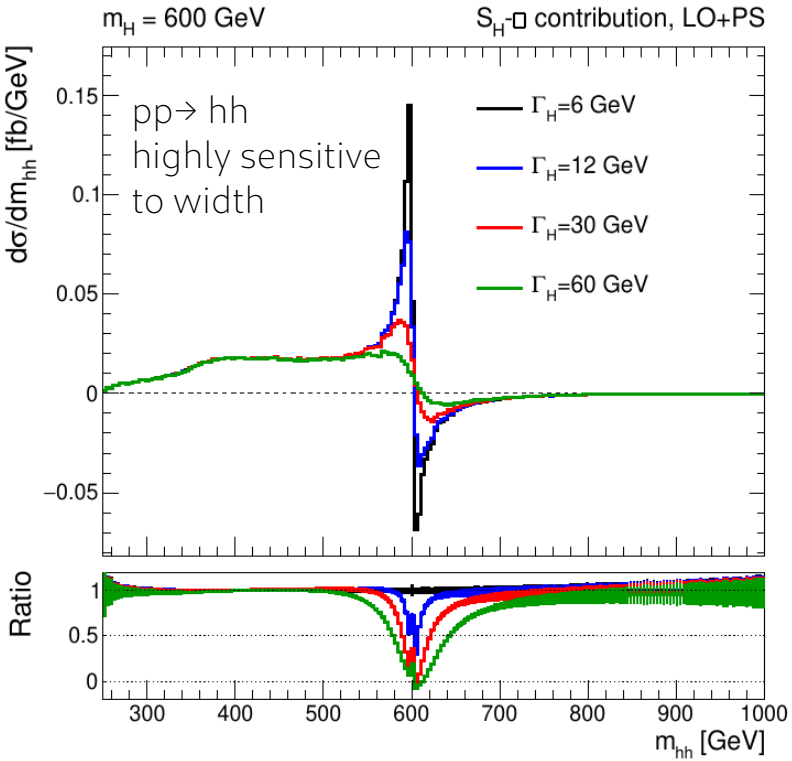
BSM triple scalar



λ_{Hhh}

Accurate (B)SM prediction of hh production crucial to interpret valuable (HL-)LHC hh data

Motivation II: the total width



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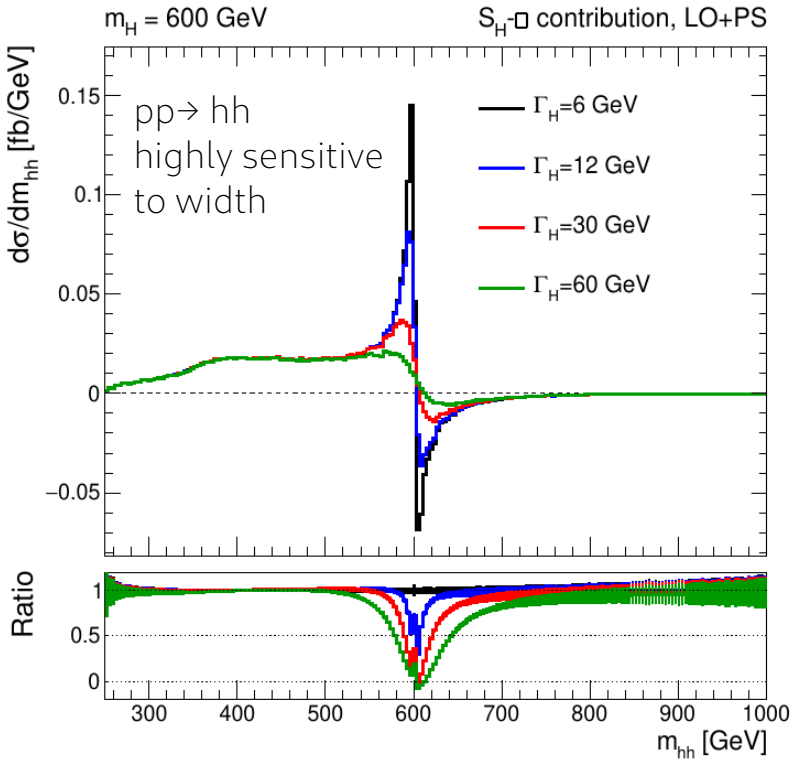
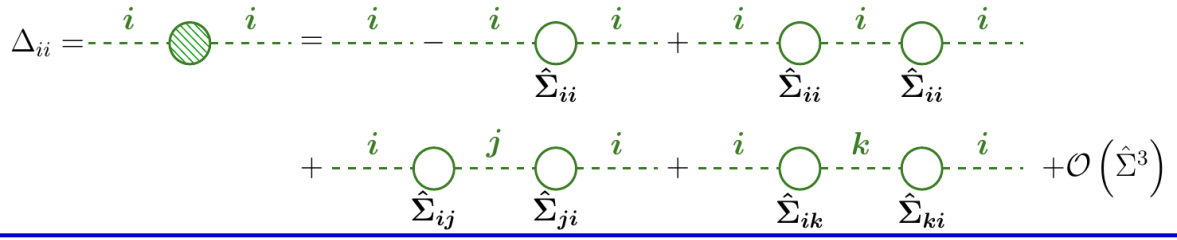


Full propagator: resummation of all self-energy insertions



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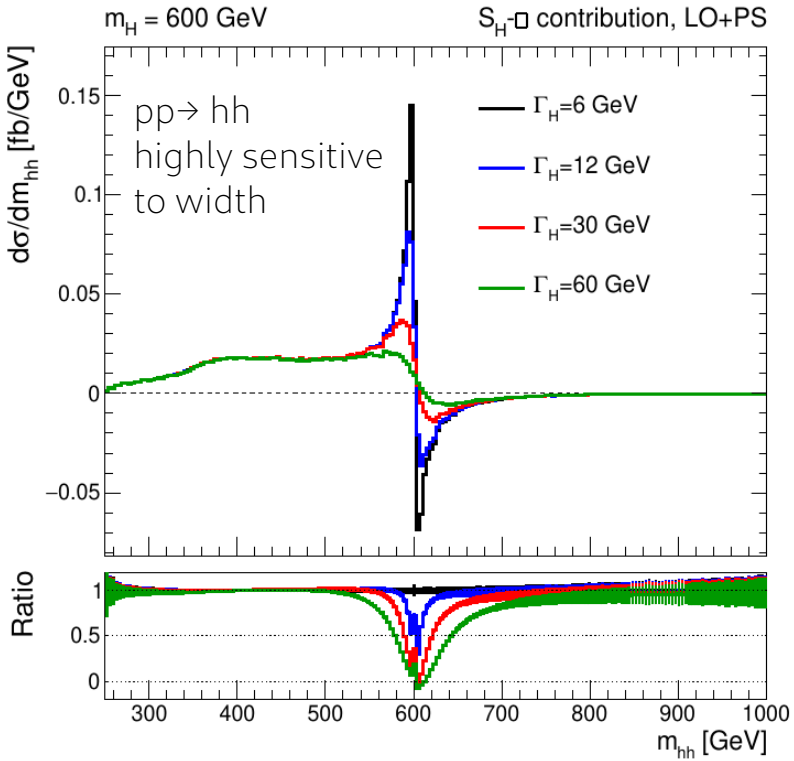

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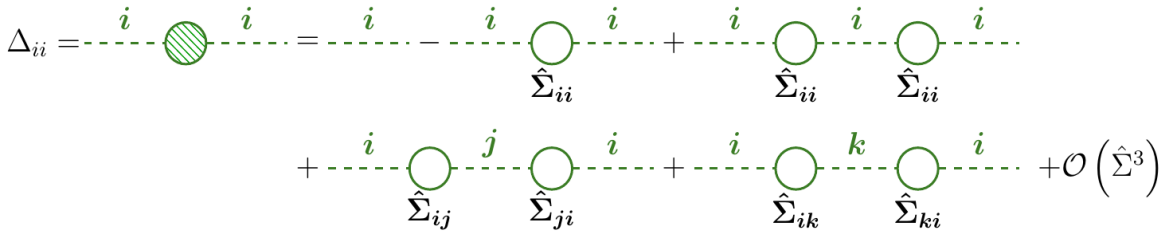

Breit-Wigner propagator of a resonance at mass m:

$$\Delta(p^2) = \frac{i}{p^2 - m^2 + im\Gamma}$$

Total width Γ determined by self-energies

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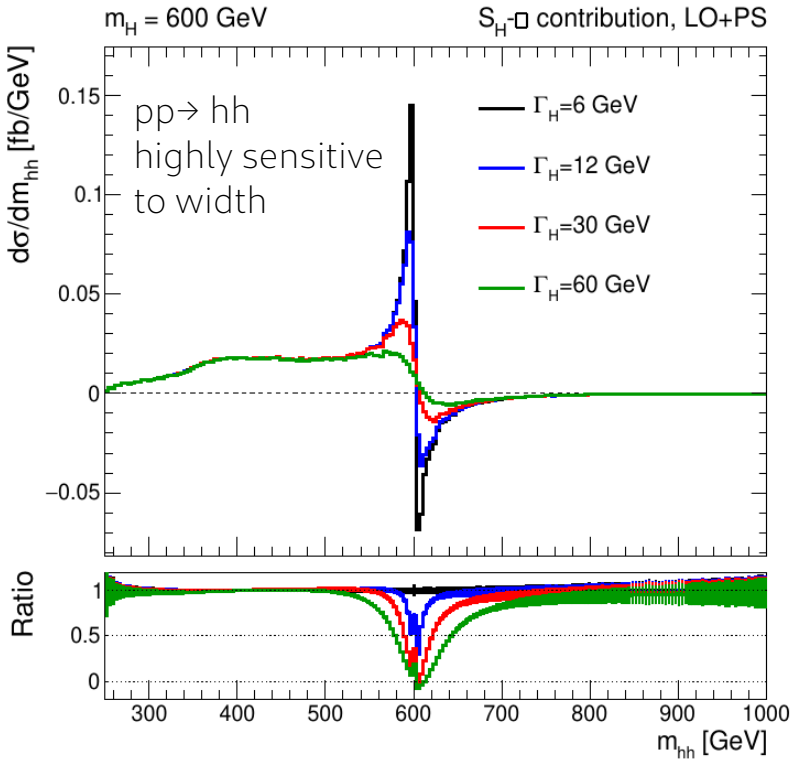

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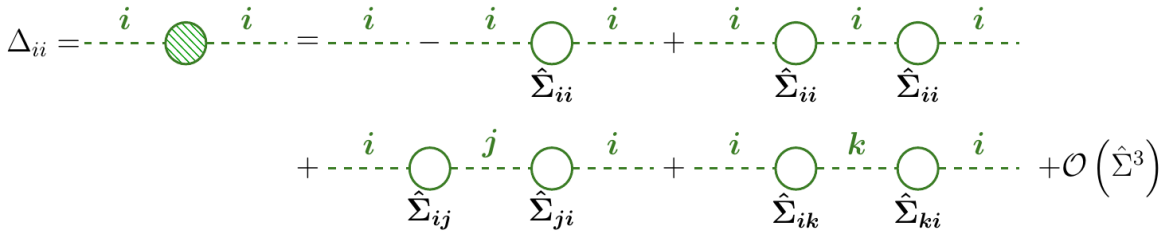


Breit-Wigner propagator of a resonance at mass m:

$$\Delta(p^2) = \frac{i}{p^2 - m^2 + im\Gamma}$$

Total width Γ determined by self-energies

The total width is a model prediction, not a free parameter, and influences the #events.

SM + Singlet

- Simplest BSM model with resonance-enhanced di-Higgs production:
  SM + singlet scalar S with $\mathbb{Z}_2$ symmetry

$$V(\Phi, S) = -m^2\Phi^\dagger\Phi - \mu^2 S^2 + \lambda_1\left(\Phi^\dagger\Phi\right)^2 + \lambda_2 S^4 + \lambda_3\Phi^2\Phi S^2$$

- 2 physical Higgs bosons: h and H
- 5 free parameters: $m_h, m_H, v, \alpha, \tan\beta = v/v_S$

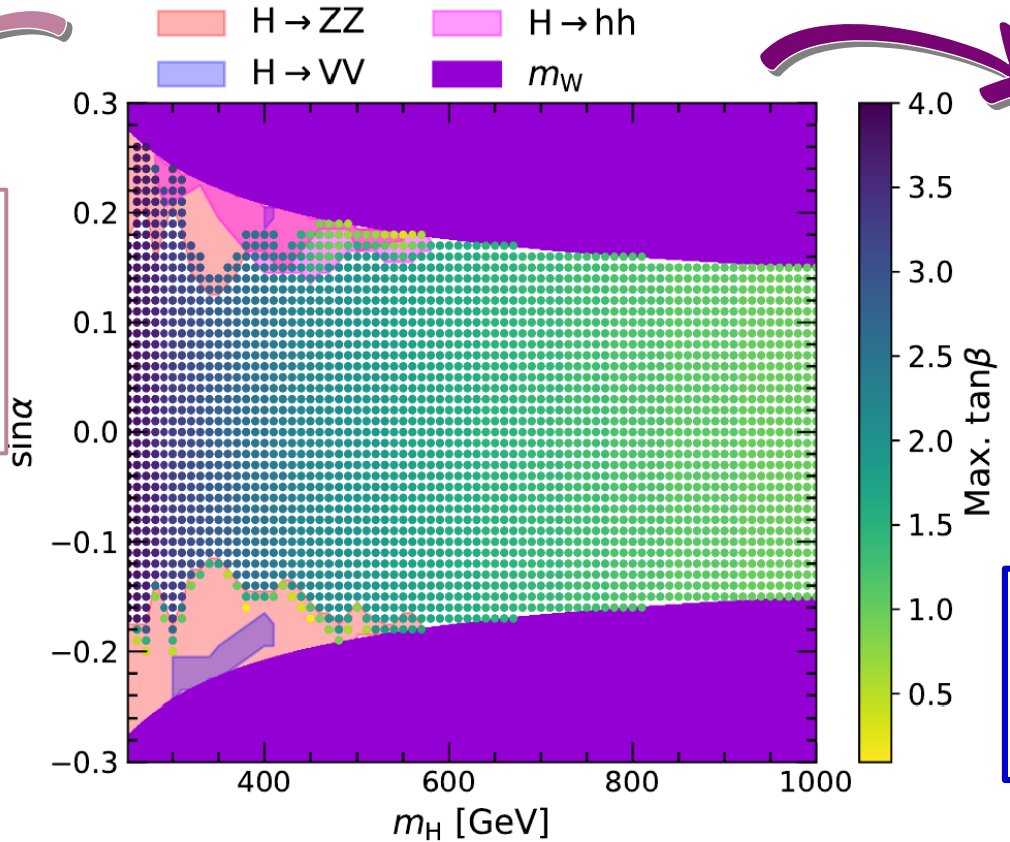
2 fixed by experiment

3 remaining free parameters

- Interested in hh final state from H→hh ⇨ choose $m_H > m_h = 125\,\mathrm{GeV}$
- Couplings of SM-like h are modified by mixing angle $\cos\alpha$

SM+S: allowed parameter space

At low m_H:
Exclusion dominated by H decays into bosons

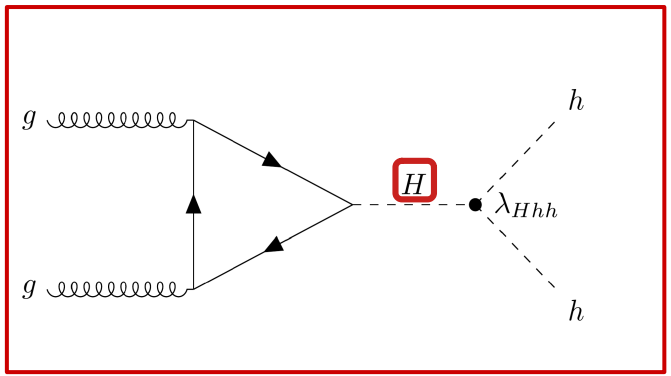


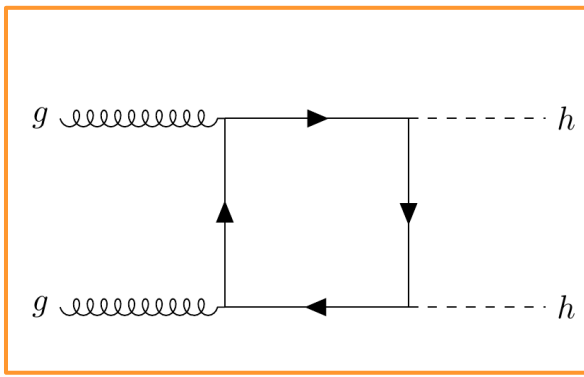
At high m_H:
Exclusion dominated by H contribution to m_W

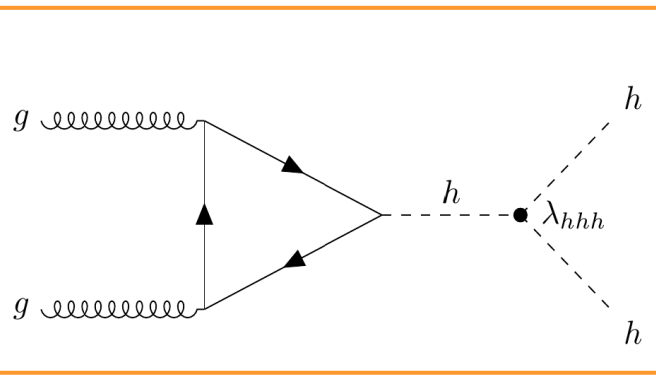
Still interesting parameter space open with sub-TeV H → understand

(Non-)resonant di-Higgs production

Total contribution of leading terms







resonant (H)

Non-resonant (withouth H)

- Investigate interference $\sigma_{\text{int}} = \sigma_{\text{total}} - (\sigma_H + \sigma_{\text{wo}H})$

Coherent sum

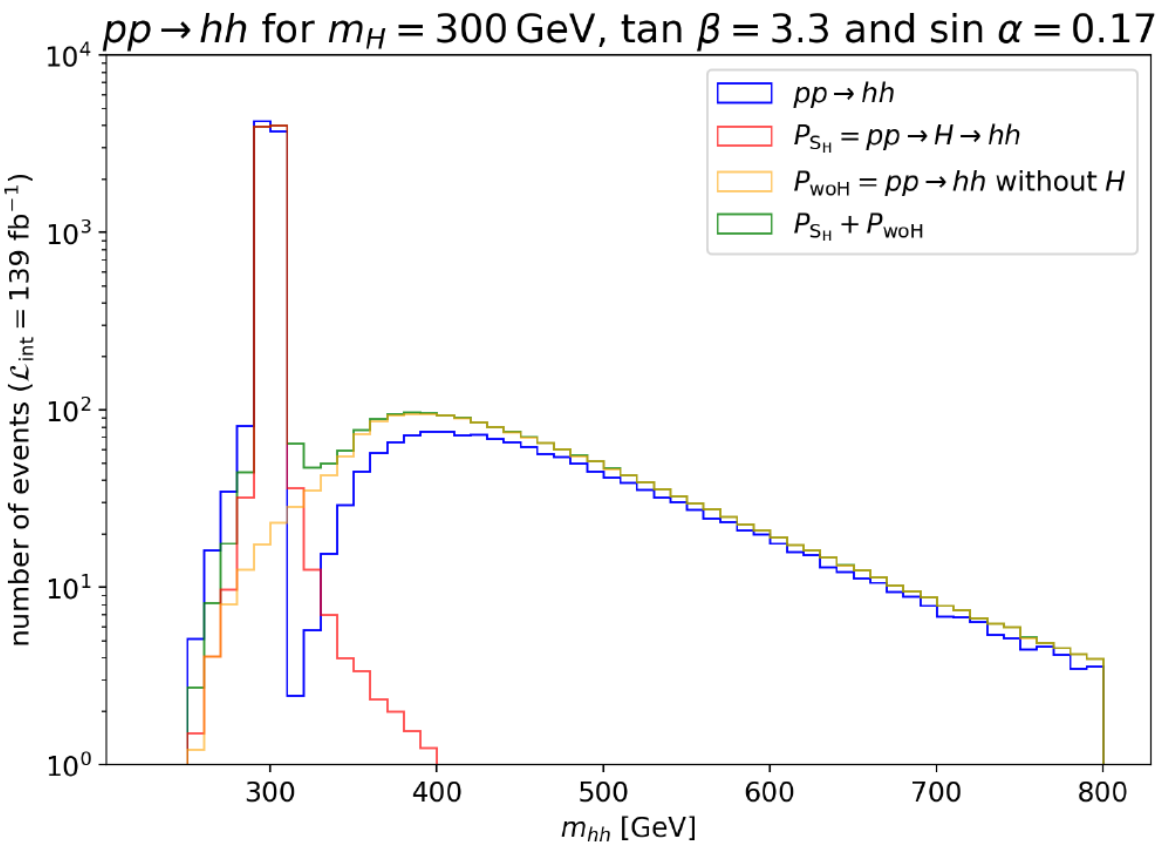
Incoherent sum

- Simulation in MadGraph based on 2-real-singlet model file (2nd singlet decoupled)

Papaefstathiou, Robens,Tetlamazi-X. JHEP 05 (2021)

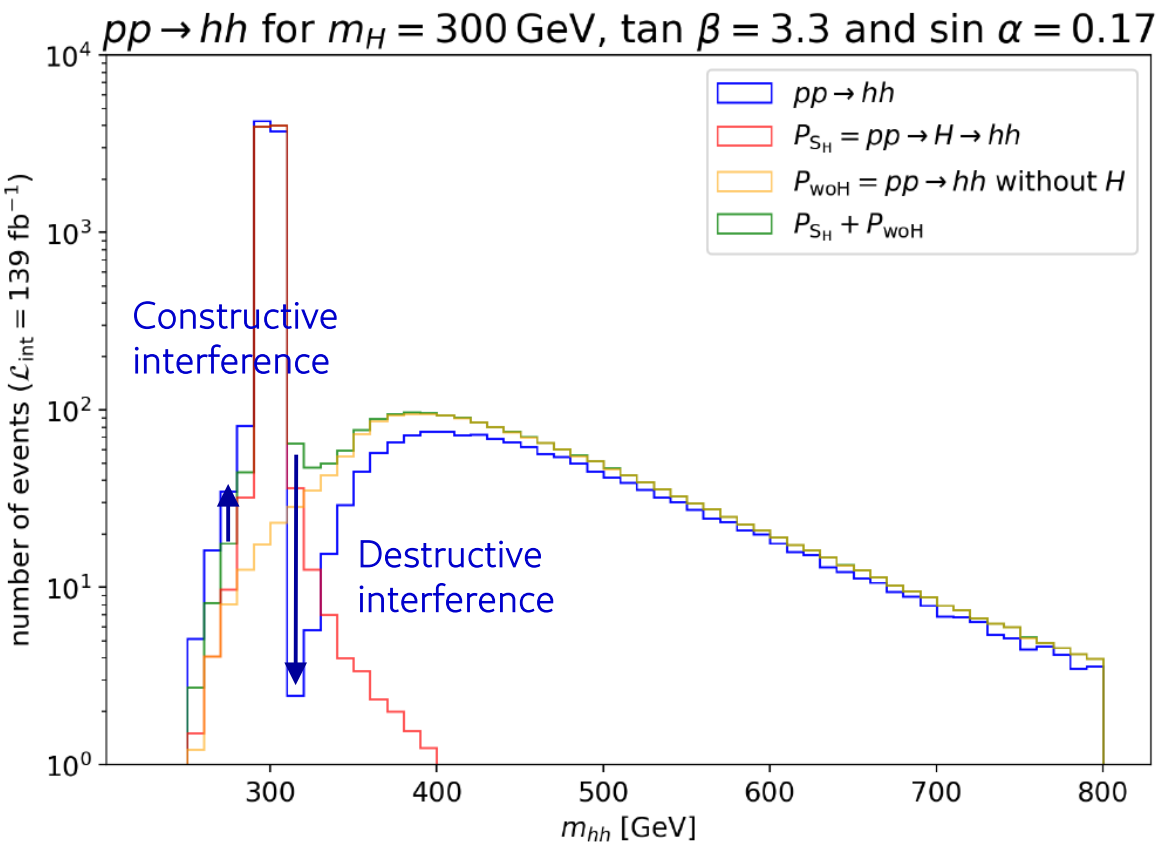
- Differential distributions: interference has significant impact on m_{hh} and p_T^h

Impact of interference on m_{hh}



} Example parameter point 1

Impact of interference on m_{hh}

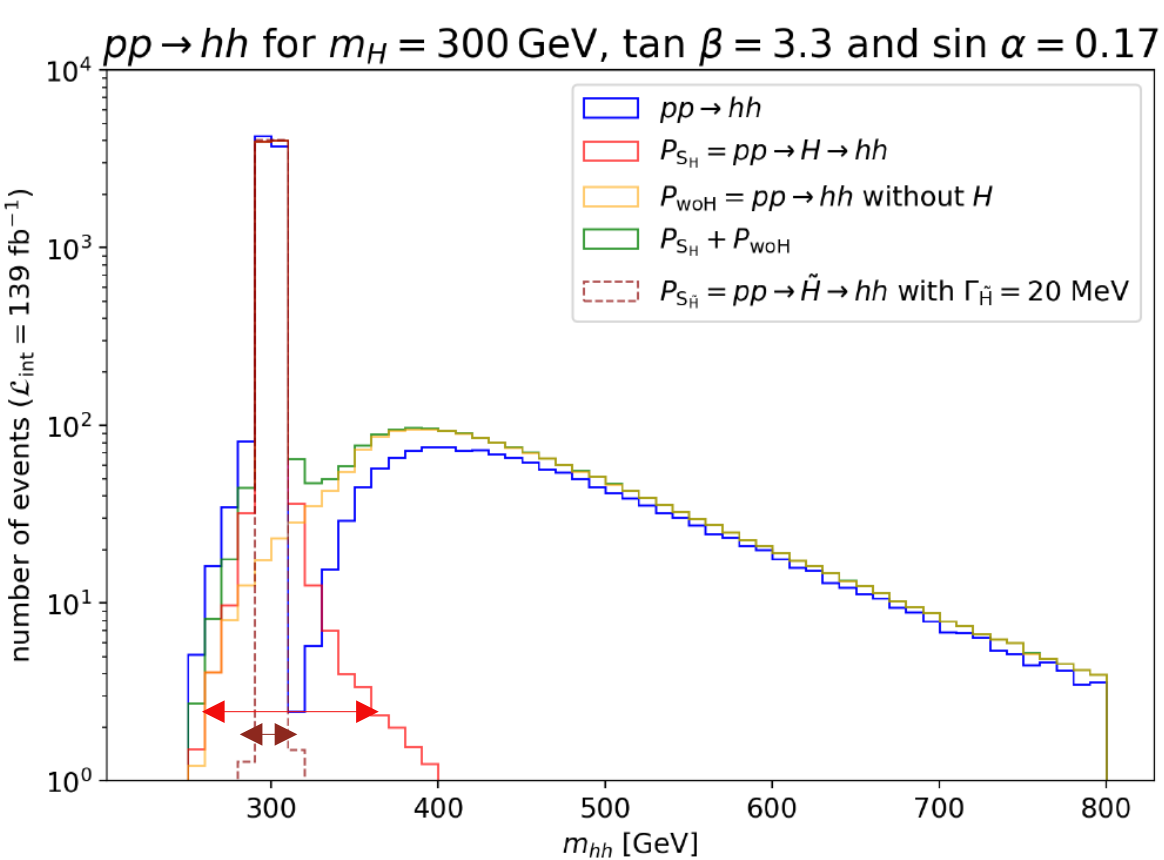


} Example parameter point 1

Well-known **peak-dip-structure** around peak at $m_{hh} \sim m_H$:

- m_{hh} < peak: positive interference
- m_{hh} > peak: negative interference

Impact of the width on m_{hh}



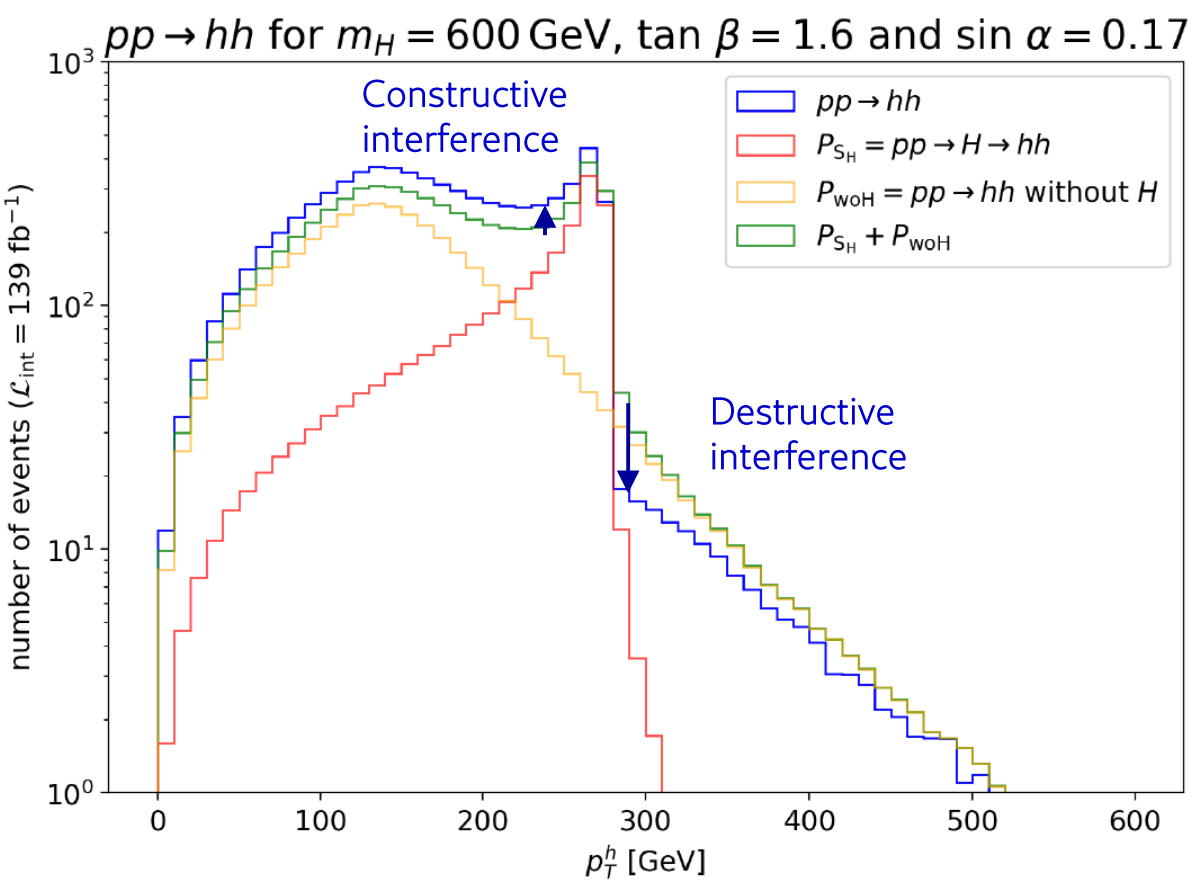
} Example parameter point 1

Plugging in a hypothetical small width by hand

- Mismatch of total cross-section
- Mismatch of distribution
- Underestimate of interference

Important to use width predicted by model at specific parameter point

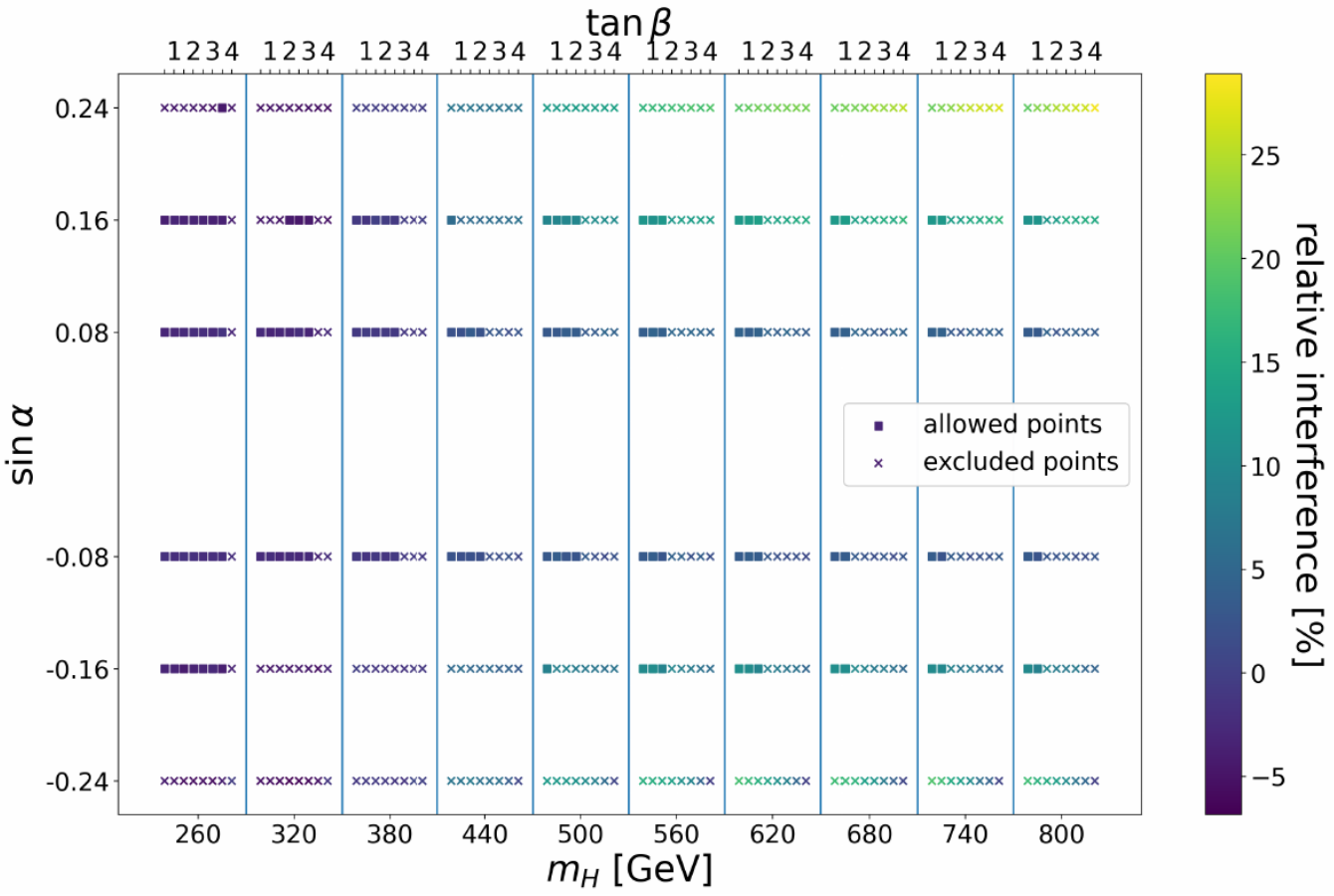
Impact of interference on p_T^h



Example parameter point 2

Besides well-known m_{hh},
also p_T^h has **peak-dip-structure**.

Relevance of interference term



How generic is a large interference in hh production in the SM+S?

Relative interference $\sigma_{int}/\sigma_{total}$ **up to 13%** among allowed points in the scan.

⇨ Motivates systematic inclusion of interference.

Need accurate and fast simulation

Motivation: Extended Higgs sector generically allow for resonant di-Higgs production

Challenge: Simulating events including interference for many parameter points in many models is numerically expensive.

Goal: Simulate components of resonant and non-resonant contributions and their interference terms to hh production only once and adapt to different models/ parameters.

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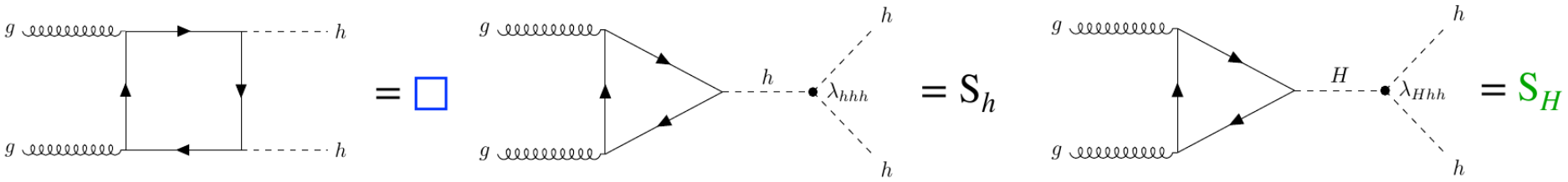
Goal: Simulate components of resonant and non-resonant contributions and their interference terms to hh production only once and adapt to different models/ parameters.

New tool: HHReweighter decomposes the LO hh matrix element into the different contributions and scales them by applicable model parameters.
NNLO K-factors used for high accuracy.

https://gitlab.com/danielwinterbottom/HHReweighter [D. Winterbottom]

→ weight $w = \frac{|\mathcal{M}_{\text{target}}|^2}{|\mathcal{M}_{\text{ref}}|^2}$

Decomposition of matrix element



$$|\mathcal{M}_{\text{total}}|^2 = \mathcal{M}_{\square}{}^2 \cdot (\kappa_q^h)^4 + \mathcal{M}_{S_h}{}^2 \cdot (\kappa_q^h)^2 \kappa_{\lambda_{hhh}}^2 \quad \text{SM events}$$

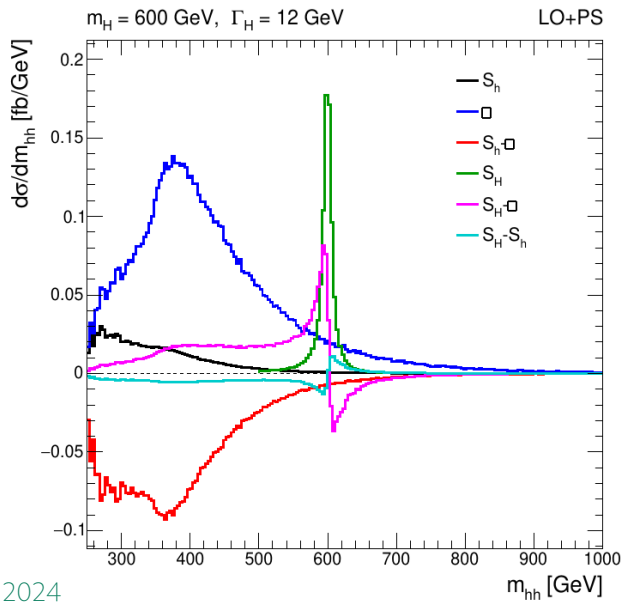
$$+ \mathcal{M}_{S_H}{}^2(m_H, \Gamma_H) \cdot (\kappa_q^H)^2 \kappa_{\lambda_{Hhh}}^2$$

$$+ \widetilde{\mathcal{M}}_{S_h-\square}{}^2 \cdot (\kappa_q^h)^3 \kappa_{\lambda_{hhh}}$$

$$+ \widetilde{\mathcal{M}}_{S_H-\square}{}^2(m_H, \Gamma_H) \cdot (\kappa_q^h)^2 \kappa_q^H \kappa_{\lambda_{Hhh}}$$

$$+ \widetilde{\mathcal{M}}_{S_H-S_h}{}^2(m_H, \Gamma_H) \cdot \kappa_q^h \kappa_q^H \kappa_{\lambda_{hhh}} \kappa_{\lambda_{Hhh}},$$

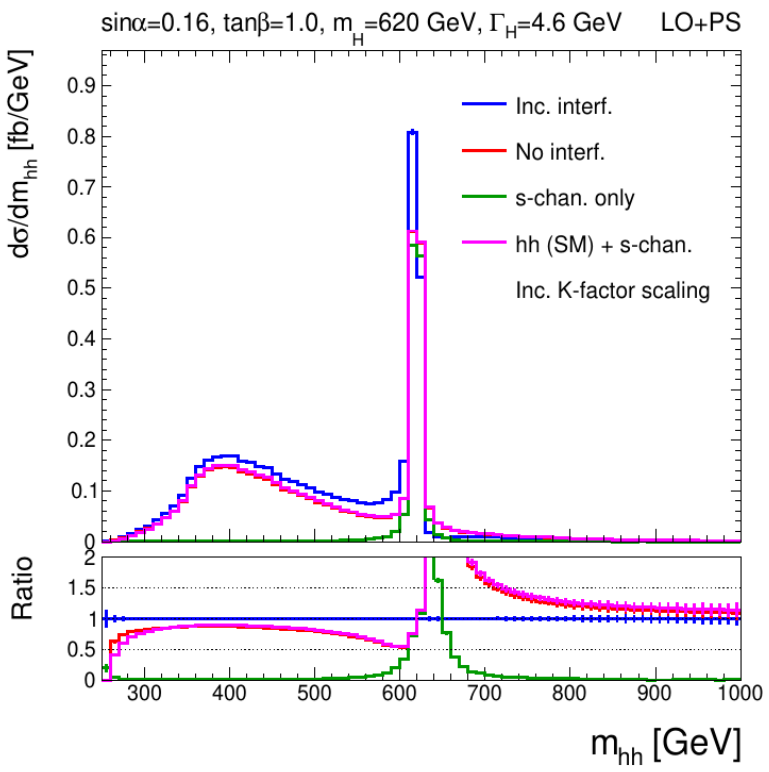
Interference terms!



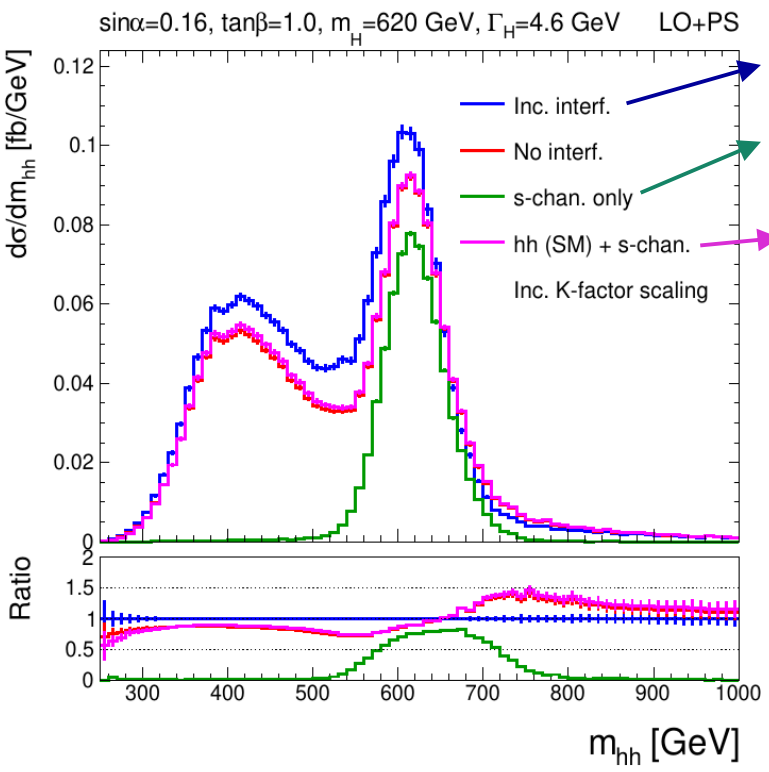
See talk by D. Winterbottom, HIGGS 2024

Interference at detector level

Developed 9 characteristic benchmarks, here **BM1: maximal relative interference**



No smearing



Smearing as for H→hh → 4b

Full result with interference $|h+H+\square|^2$

Resonant only $|H|^2$ (most analyses so far)

Incoherent sum $|H|^2 + |h+\square|^2$ (BSM, SM) (some analyses so far)

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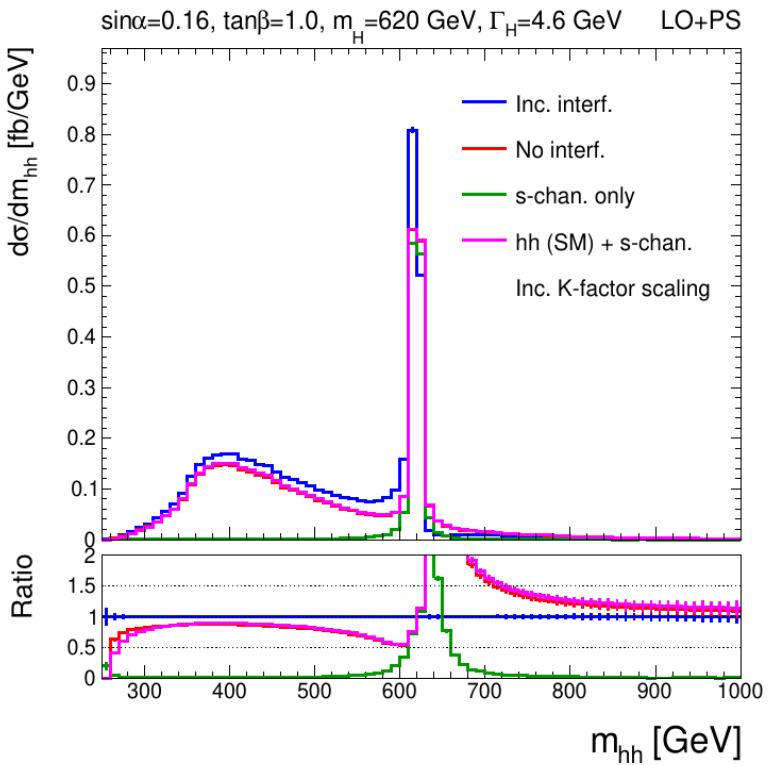

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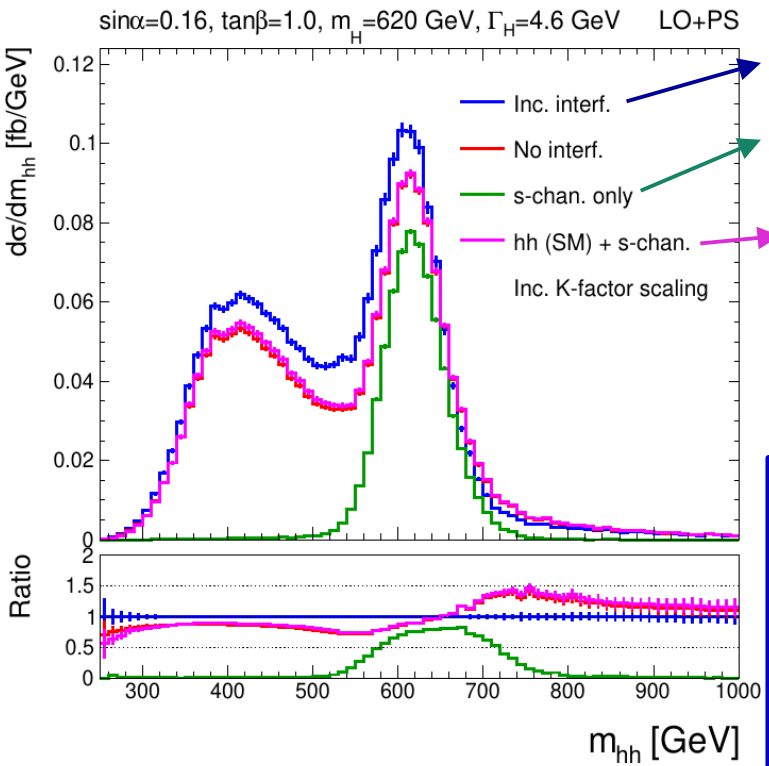

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after smearing:

- interference persists
- double peak
- $|H|^2$ only under-estimates events close to peak by 35%

Further benchmarks

Benchmark	$\sin\alpha$	$\tan\beta$	m_H [GeV]	Γ_H [GeV]	$\kappa_{\lambda_{hhh}}$	σ [fb]	$\sigma_{\mathrm{S_H}}$ [fb]	Accessible in Run-3	Feature
BM1	0.16	1.0	620	4.6	0.96	50.5	13.5	✓	Max $(\Delta\sigma)_{\mathrm{rel}}$
BM2	0.16	0.5	440	1.5	0.96	91.6	56.4	✓	Max $(\Delta\sigma)^{\sum}_{\mathrm{rel}}$
BM3	0.16	0.5	380	0.8	0.96	119.8	90.1	✓	Max $(\Delta\sigma)^{\sum}_{\mathrm{rel}}$ with $(\Delta\sigma)_{\mathrm{rel}} < 1\%$
BM4	-0.16	0.5	560	3.0	0.96	51.4	15.5	✓	Max non-res. within $m_H \pm 10\%$
BM5	0.08	0.5	500	0.6	0.99	40.6	8.1		Max non-res. within $m_H \pm 10\%$
BM6	0.16	1.0	680	6.1	0.96	44.8	8.4	✓	Max m_H
BM7	0.15	1.1	870	9.5	0.96	36.8	2.3		Max m_H
BM8	0.24	3.5	260	0.6	0.87	374.2	357.3	✓	Max $\lvert\kappa_{\lambda_{hhh}} - 1\rvert$
BM9	0.16	1.0	800	9.8	0.96	38.9	3.6		Max $\frac{\Gamma_H}{m_H}$

Conclusions

1. Finite-width and interference effects are relevant and need to be taken into account also in hh.

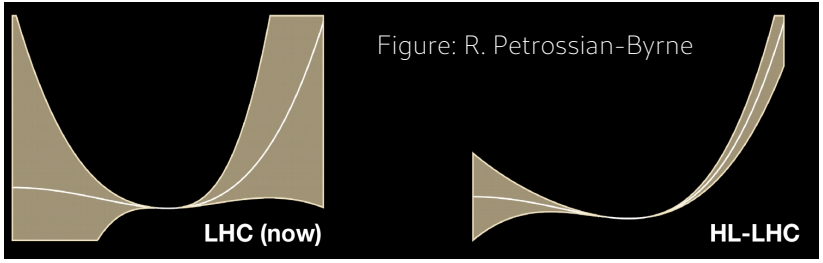
2. The SM+S features relevant interference between resonant & non-resonant di-Higgs production.

3. Beyond m_{hh}, among the investigated distributions, p_T^h is most sensitive to interference.

4. We provide bounds on SM+S and 9 characteristic benchmarks.
   - Here: BM1 with maximal interference (<13%).
   - See other benchmarks for effects of the total width, self-coupling modification, and cancellation of interference before/ after peak.

5. We introduce a new public tool HHReweighter to reweigh matrix elements for a fast & accurate inclusion of interference effects incl. K-factors in various models.

Future experimental precision of hh requires precise and accurate theory predictions!



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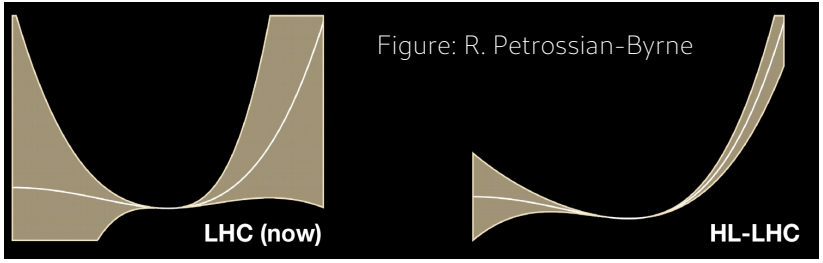
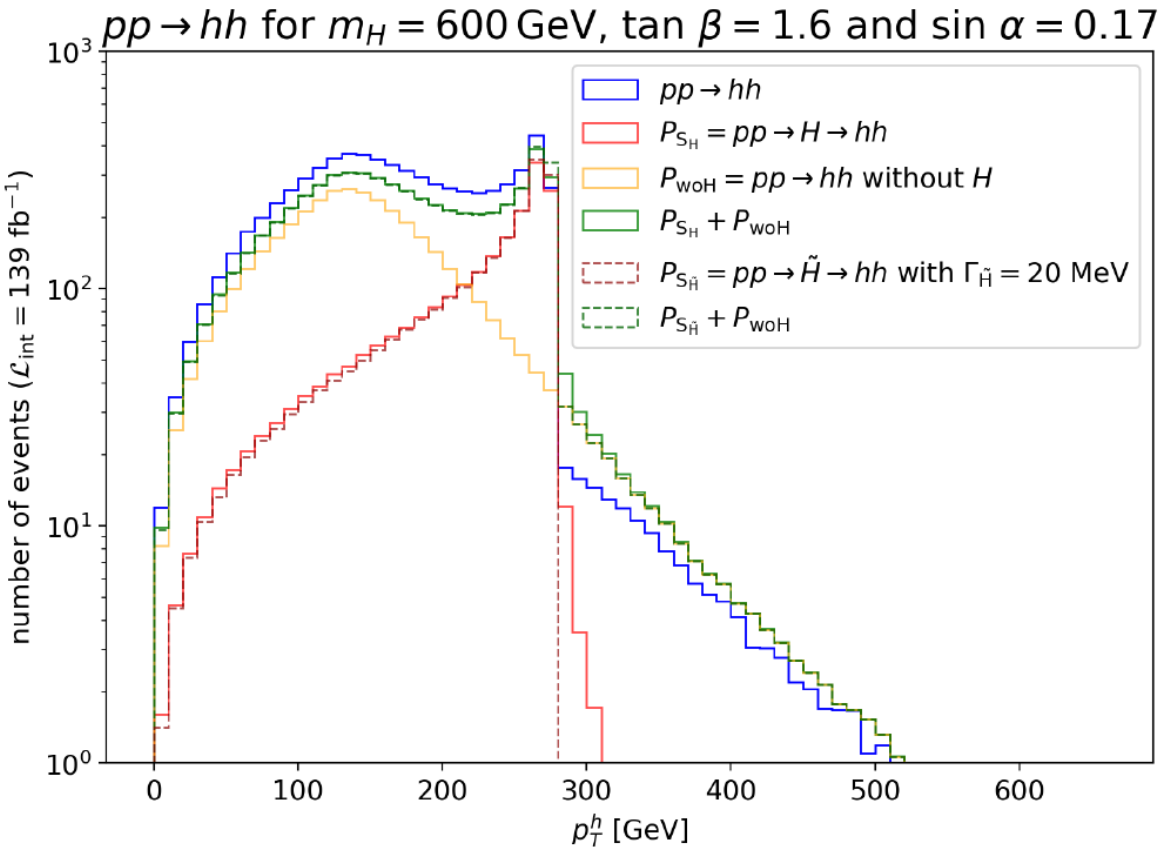


BACKUP

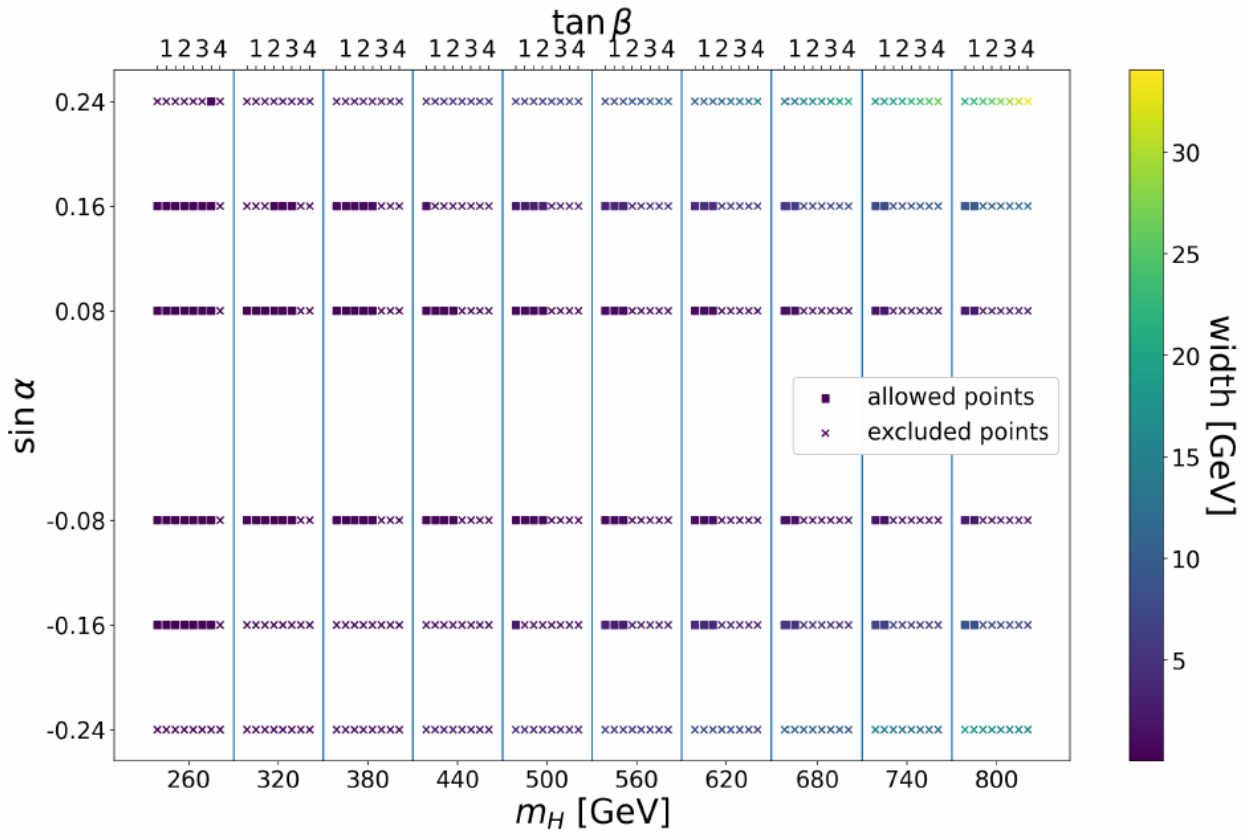
Impact of total width on p_T^h



Small hypothetical width

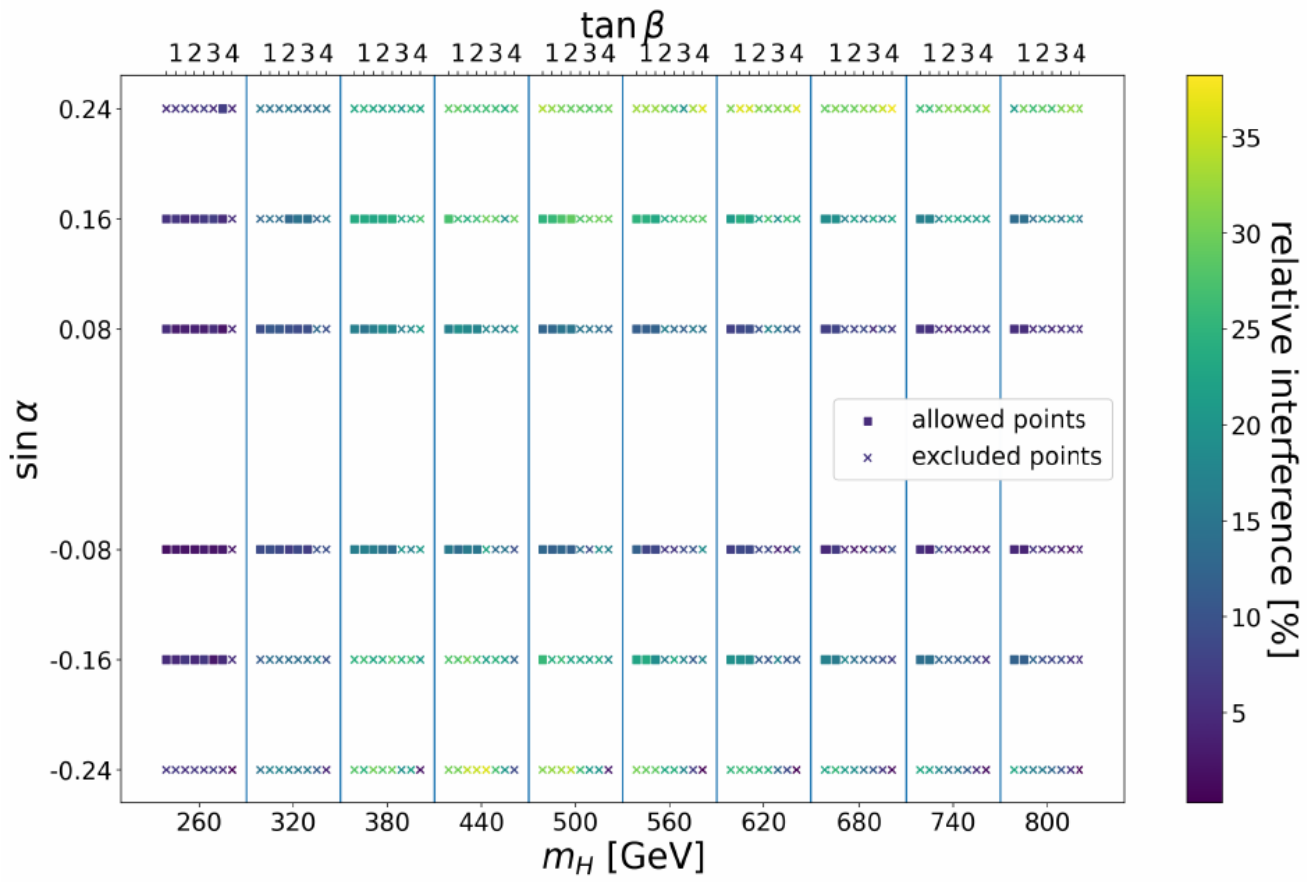
- Underestimates #events after the peak
- Underestimates interference

Total width Γ_H



Within allowed points of the scan:
$\Gamma_H/m_H < 0.012$

Relative interference before/after peak

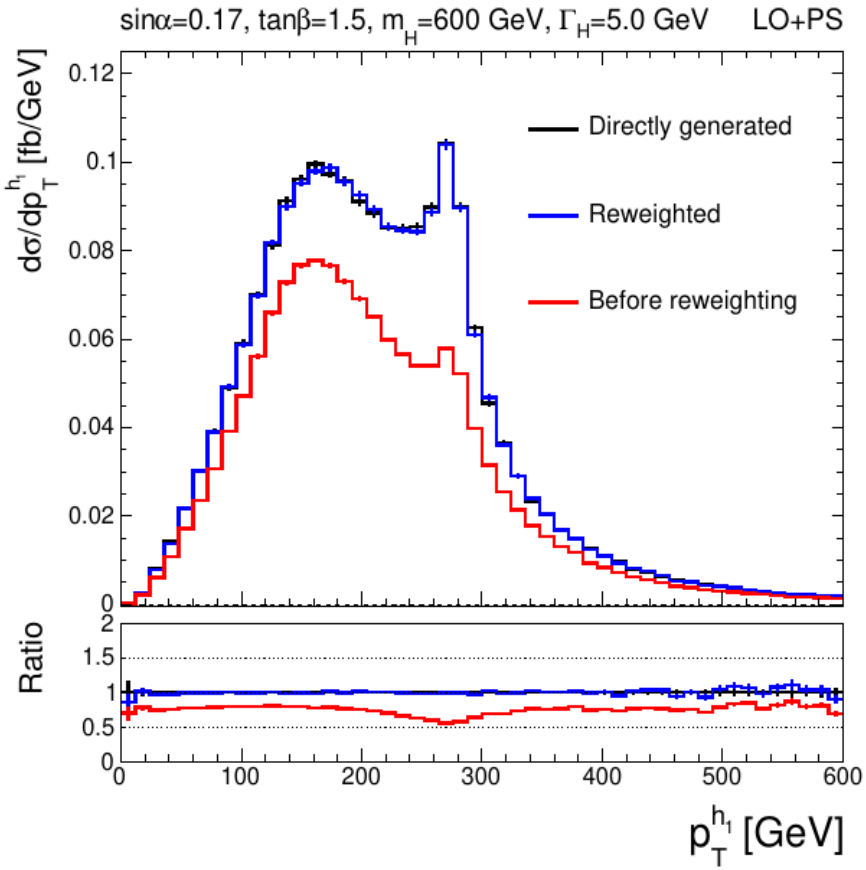


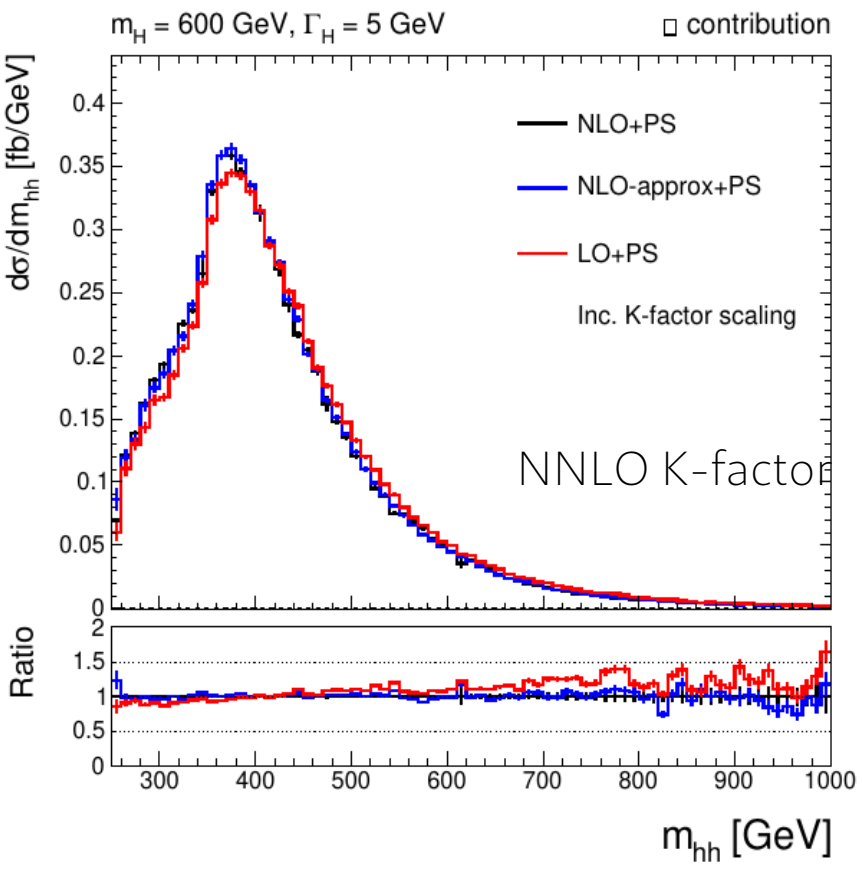
(f) The relative interference sum

$$(\Delta\sigma)^{\sum}_{\text{rel}} = \left|(\Delta\sigma)^{<}_{\text{rel}}\right| + \left|(\Delta\sigma)^{>}_{\text{rel}}\right|.$$

Larger effect on distribution than on total cross section.

Validation of HHReweighter





SM+S model predictions

$$\Gamma_H = \sin^2\alpha\,\Gamma_{\rm SM}(m_H) + \frac{\lambda_{Hhh}^2\sqrt{1-4m_h^2/m_H^2}}{8\pi m_H}$$

$$\kappa_q'' = \cos\alpha,$$

$$\kappa_q^H = \sin\alpha,$$

$$\lambda_{\rm SM} = \frac{m_{125}^2}{2\,v}$$

$$\lambda_{hhh} = \lambda_{\rm SM}\left(\cos^3\alpha - \tan\beta\sin^3\alpha\right),$$

$$\lambda_{Hhh} = \lambda_{\rm SM}\frac{2m_h^2+m_H^2}{m_h^2}\,\frac{\sin(2\alpha)}{2}\left(\cos\alpha+\tan\beta\sin\alpha\right)$$