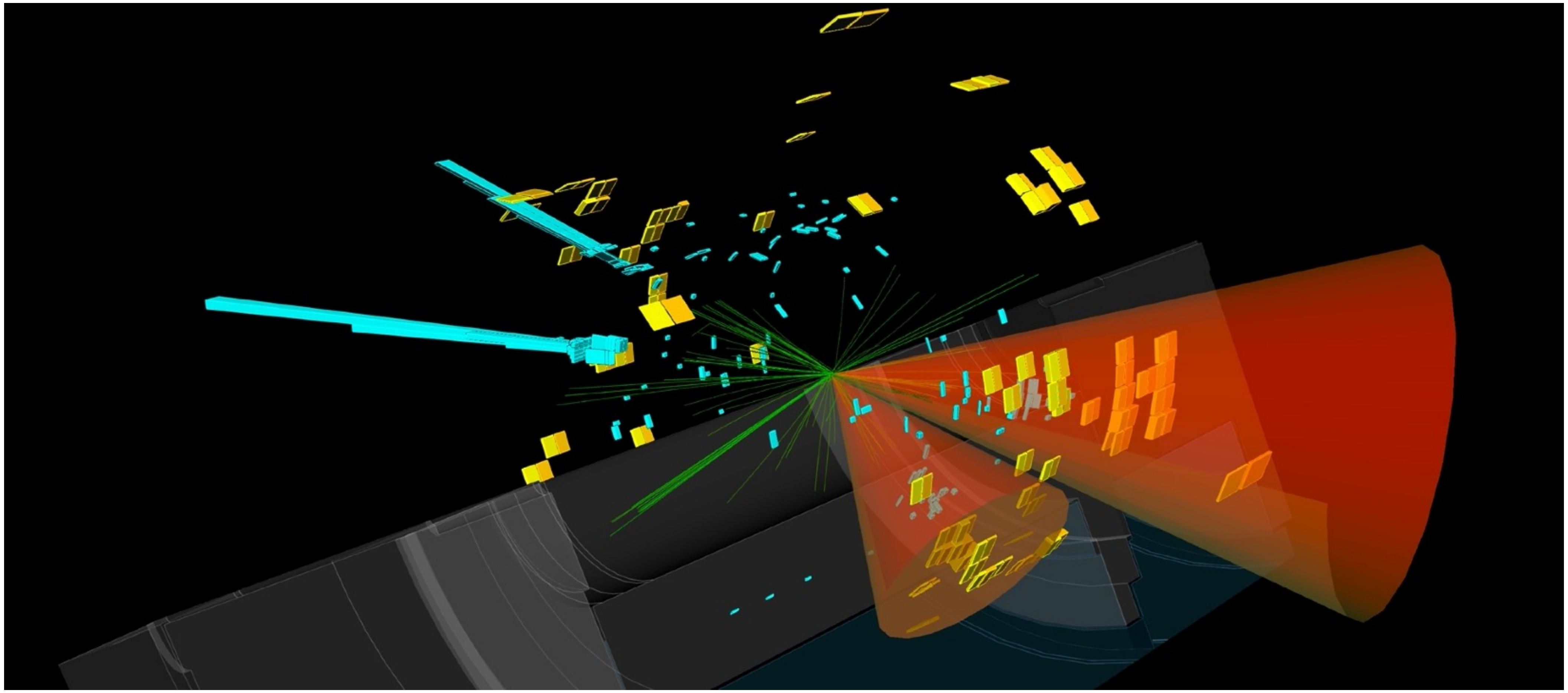
IMPERIAL

Interference effects in resonant di-Higgs production at the LHC



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Overview

- The material shown today based on the paper "**Interference effects in resonant di-Higgs production at the LHC in the Higgs singlet extension**", in collaboration with F. Feuerstake, E. Fuchs, and T. Robens
    - arXiv:2409.06651
- Latest bounds on Higgs singlet model
- Investigation of interference effects on HH mass spectrum and other variables such as Higgs p_T
- New tool for modelling interference effects using matrix element (ME) reweighing
- Introducing several benchmark scenarios that exhibit interesting features (e.g large interference effects)

The Higgs singlet model

- Simplest extension of the Standard model (SM) that can provided resonance-enhanced di-Higgs production = Higgs singlet model with softly broken $\mathbb{Z}_2$ symmetry

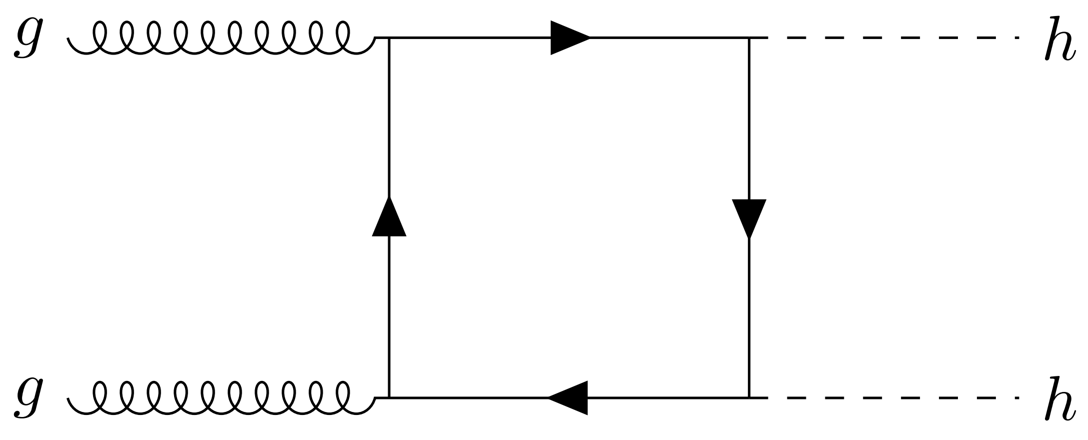
- Potential: $V(\Phi, S) = -m^2\Phi^\dagger\Phi - \mu^2 S^2 + \lambda_1 \left(\Phi^\dagger\Phi\right)^2 + \lambda_2 S^4 + \lambda_3 \Phi^\dagger\Phi S^2$

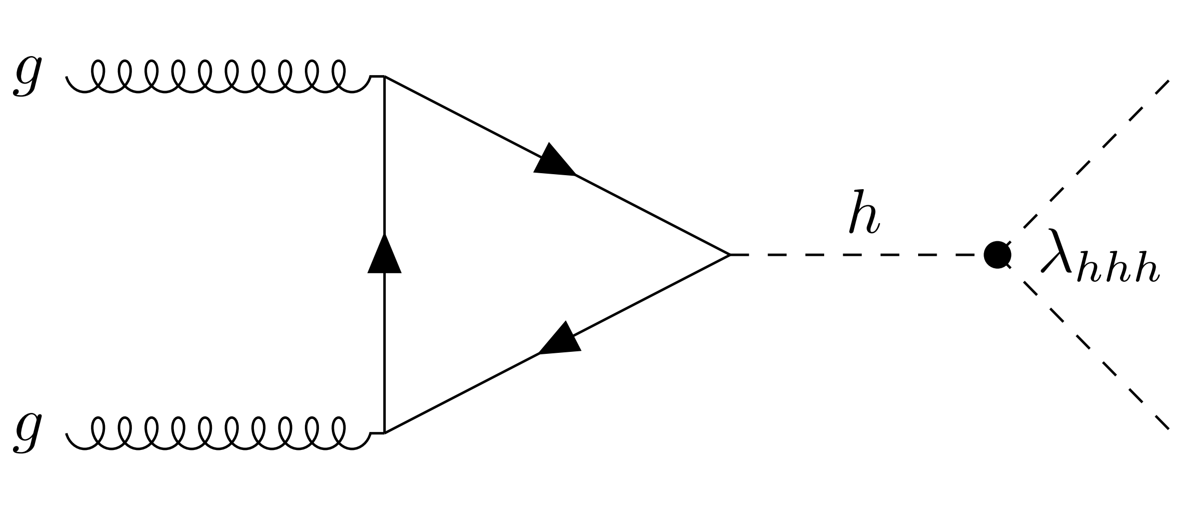
- 5 free parameters
  - 2 of them fixed by experiments: v and m_h=125 GeV
  - 3 remaining parameters chosen as: m_H, $\sin\alpha$, $\tan\beta = \mathrm{v}/\mathrm{v}_S$
  - α is mixing angle that rotates gauge into mass eigenstates, define $m_H > m_h$

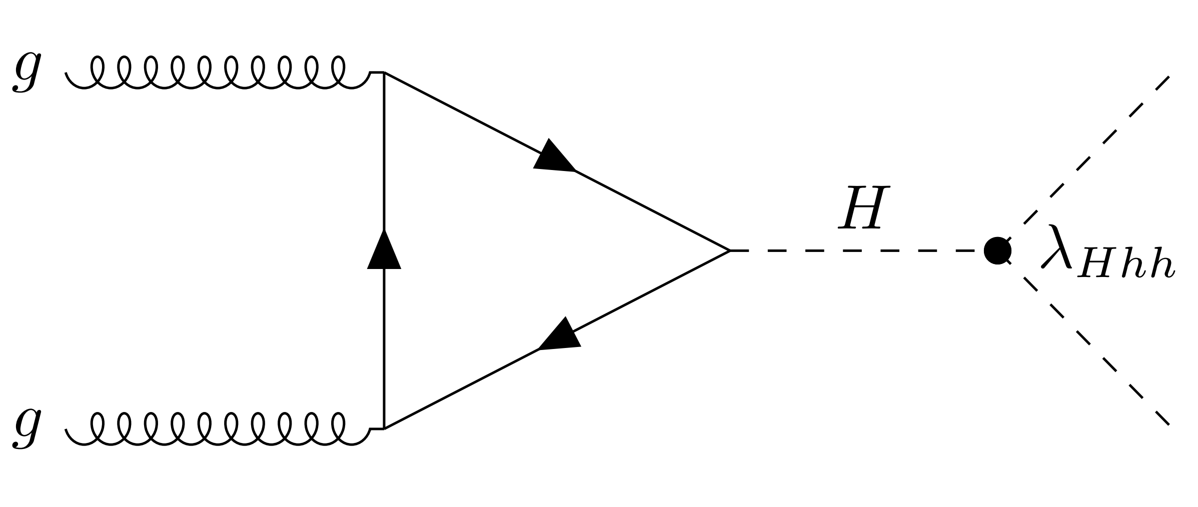
- SM-like h couplings to fermions and weak gauge bosons modified by $\cos\alpha$

- Heavy Higgs H behaves like SM-Higgs with couplings to fermions and gauge bosons scaled by $\sin\alpha$, with additional decay channel (if $m_H > 2m_h$): H→hh

- Dominant diagrams contributing to di-Higgs spectrum
- Interference between diagrams as well!







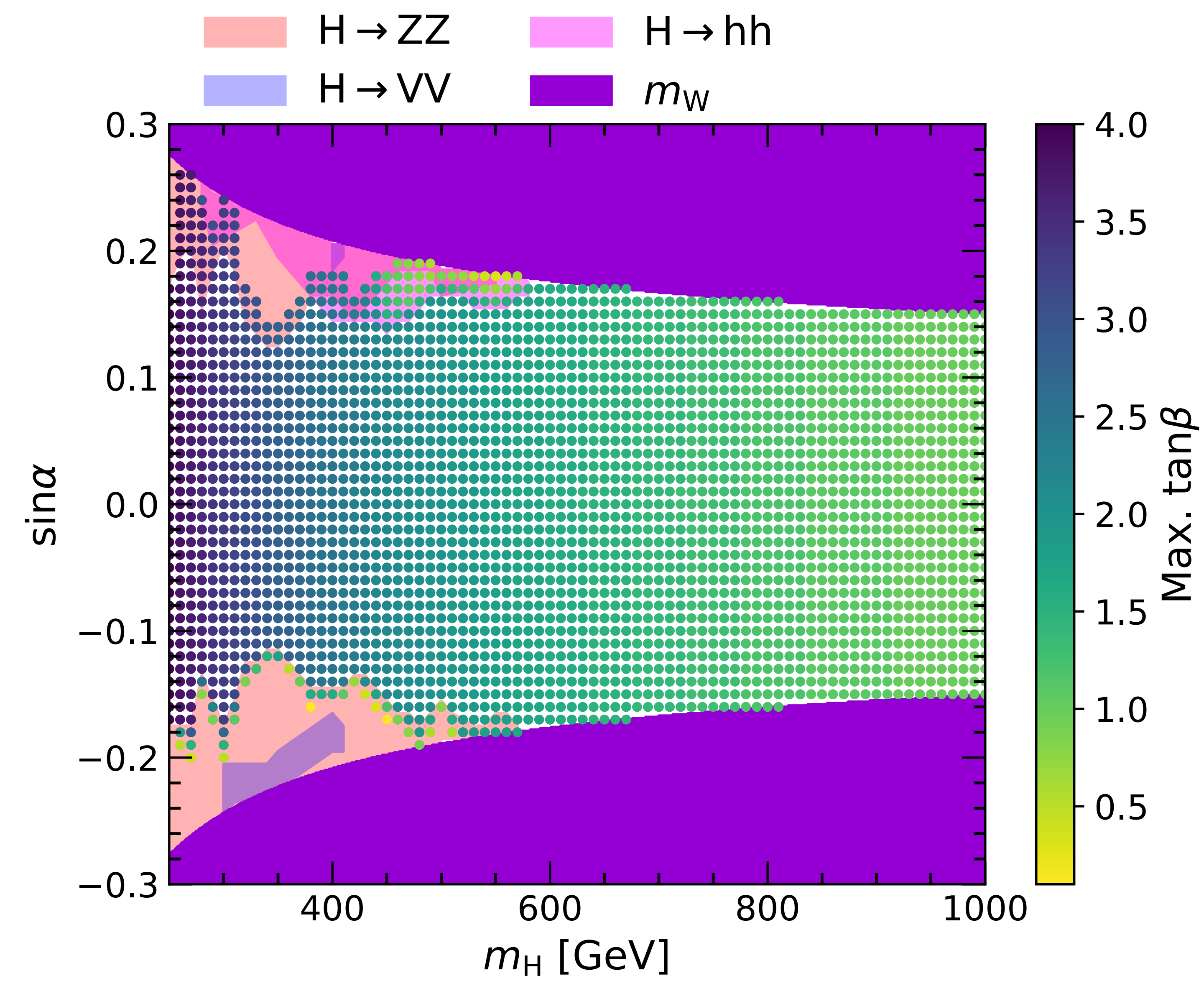
Allowed parameter space

- Investigate allowed regions

- Theory bounds: unitarity, EW precision data, perturbativity of the couplings, boundedness from below of the potential, local minimum of the potential

- At high m_H, points excluded by W mass measurement

- At low m_H point excluded by experimental searches: mainly H→ZZ and H→hh



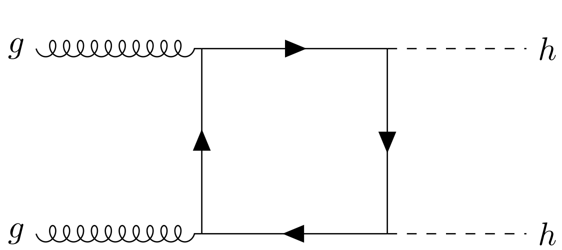
ME reweighing method

- ME reweighing reweighs events using:

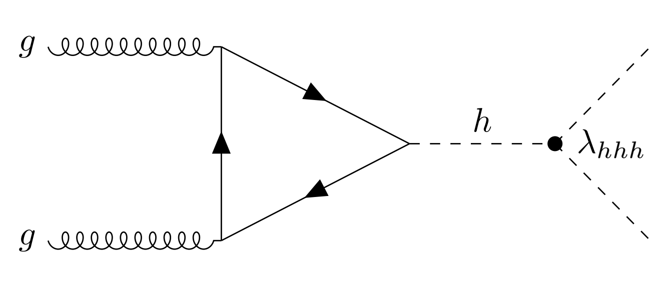
$$w = \frac{|\mathcal{M}_{\text{target}}|^2}{|\mathcal{M}_{\text{ref}}|^2}$$

- $\mathcal{M}_{\text{ref}}$ is ME for the MC you are reweighing and $\mathcal{M}_{\text{target}}$ is the ME for the process/parameters you want to model
    - $\mathcal{M}_{\text{target}}$ in general model dependent, many options for process and parameters
    - In our method we decompose $\mathcal{M}_{\text{target}}$ into minimal set of contributions that can scaled and combined to obtain distributions in any model
- Matrix elements computed using MadGraph with TRSM (A Papaefstathiou, T Robens and G Tetlalmatzi-Xolocotzi JHEP05(2021)193)

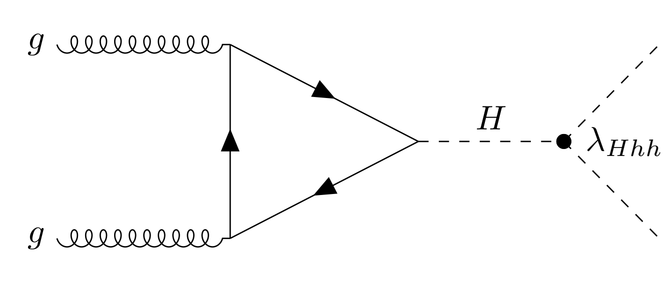
Decomposing the ME



$= \Box$



$= S_h$

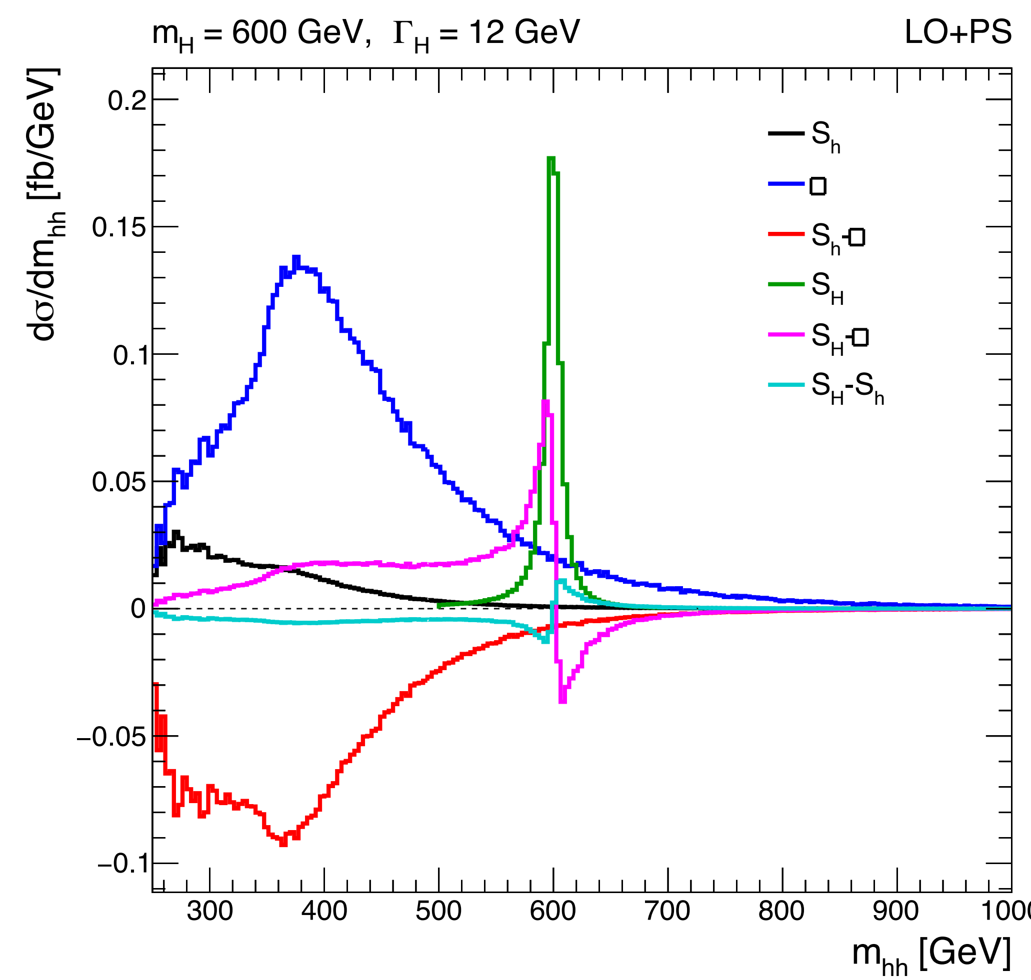


$= S_H$

Parameterise using: $\lambda_{hhh}, \lambda_{Hhh}, y_q^h, y_q^H, \Gamma_H, m_H$ **(**$\kappa_p = p/p_{SM}$**)**

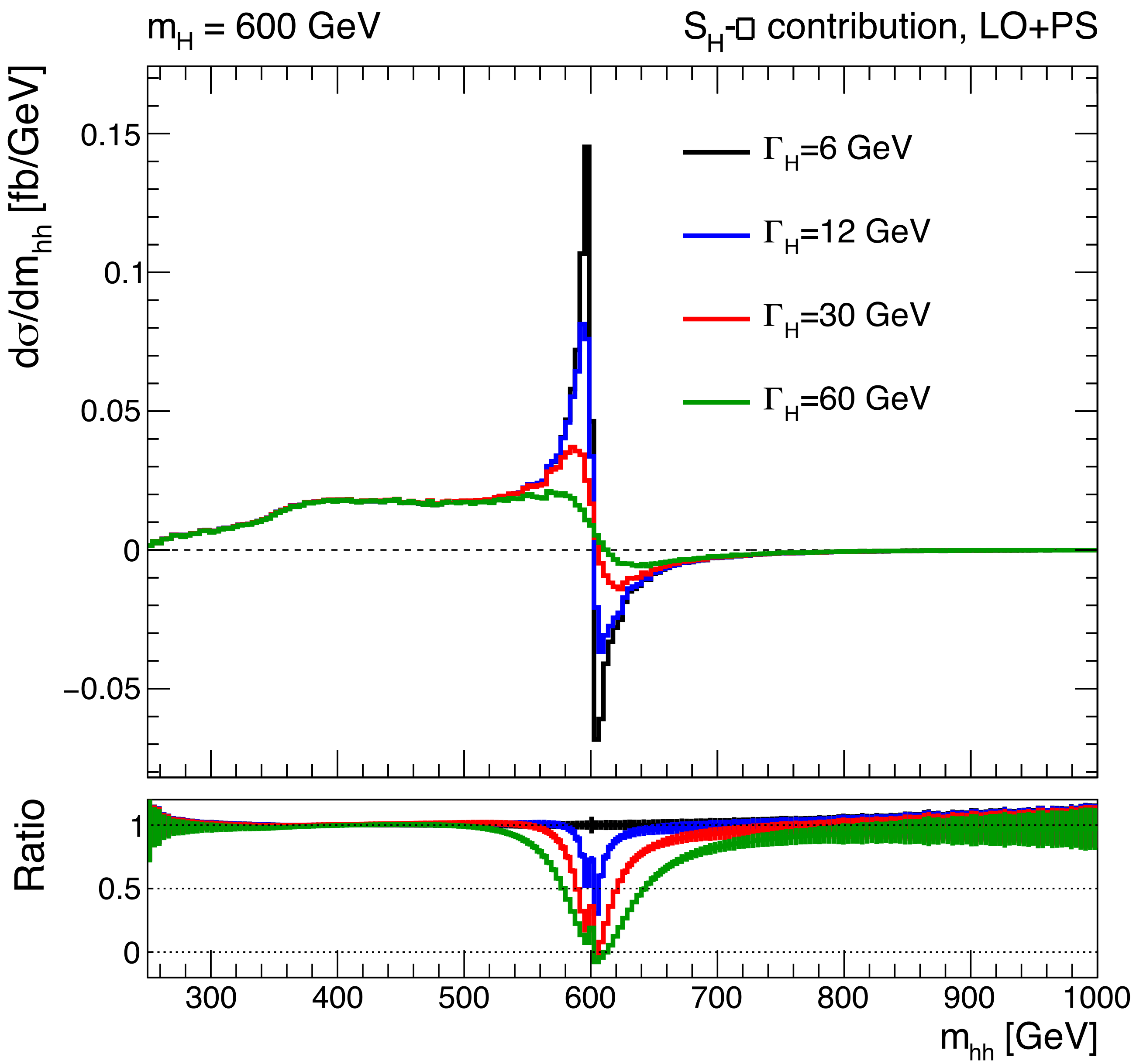
$$
\begin{aligned}
|\mathcal{M}_{\text{total}}|^2 = {} & \mathcal{M}_{\Box}^{\,2} \cdot (\kappa_q^h)^4 \\
& + \mathcal{M}_{S_h}^{\,2} \cdot (\kappa_q^h)^2 \kappa_{\lambda_{hhh}}^2 \\
& + \mathcal{M}_{S_H}^{\,2}(m_H, \Gamma_H) \cdot (\kappa_q^H)^2 \kappa_{\lambda_{Hhh}}^2 \\
& + \widetilde{\mathcal{M}}_{S_h - \Box}^{\,2} \cdot (\kappa_q^h)^3 \kappa_{\lambda_{hhh}} \\
& + \widetilde{\mathcal{M}}_{S_H - \Box}^{\,2}(m_H, \Gamma_H) \cdot (\kappa_q^h)^2 \kappa_q^H \kappa_{\lambda_{Hhh}} \\
& + \widetilde{\mathcal{M}}_{S_H - S_h}^{\,2}(m_H, \Gamma_H) \cdot \kappa_q^h \kappa_q^H \kappa_{\lambda_{hhh}} \kappa_{\lambda_{Hhh}},
\end{aligned}
$$

Interference terms!



Dependence on the width

- S_H, $\square - S_H$, and $S_H - S_h$ depend on the mass and the width of the H



Technical detail

- With ME reweighing you need to make sure your chosen reference sample is populated in all phase-space regions where $\mathscr{M}_{\text{target}}$ is non-vanishing

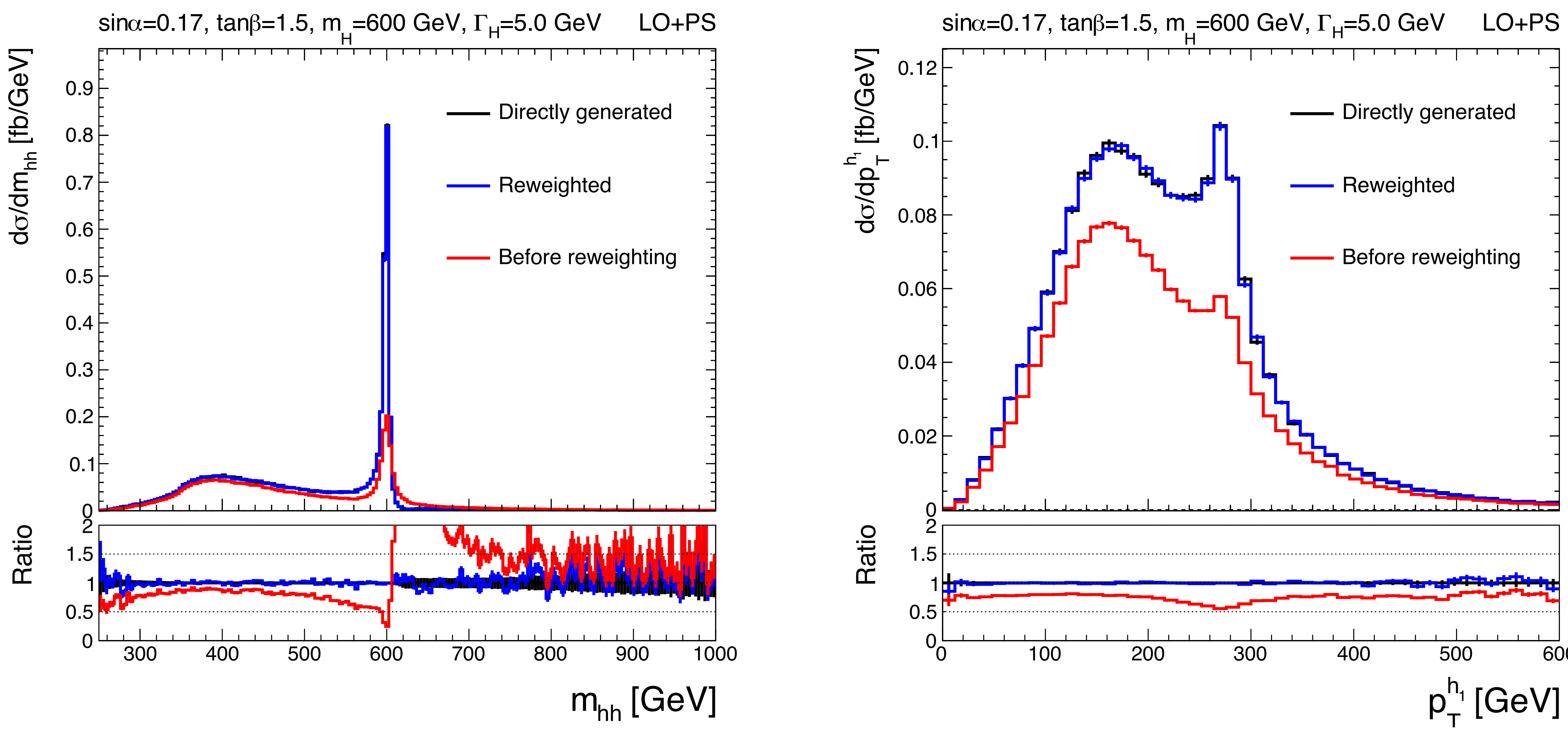
- For the $\square$, S_h, $\square - S_h$, $\square - S_H$, and $S_H - S_h$ contributions we use a SM di-Higgs sample (non-resonant only)

- For S_H we use a MC samples of the same m_H and a width not too far from the target (~0.5–2 x target Γ_H)

- All LO MC sample generated using Madgraph with TRSM

Validating the reweighing method

- Applying reweighing to LO MC samples give ~perfect agreement with samples generated for a set of model points!



Including higher-order corrections

- For gluon fusion LO know to under predict cross-section (XS) by ~200-300%
- We can correct for this using K-factors
- K-factors for SM-like terms derived using NNLO XSs from LHCHWG4 (link)
- K-factors for S_H derived using (NNLO+NNLL) XSs for undecayed H production from LHCHWG (here)
- For interference terms use ansatz: $K_{i-j} = \sqrt{K_i K_j}$

Benchmarks

- Several new benchmarks defined that exhibit interesting features

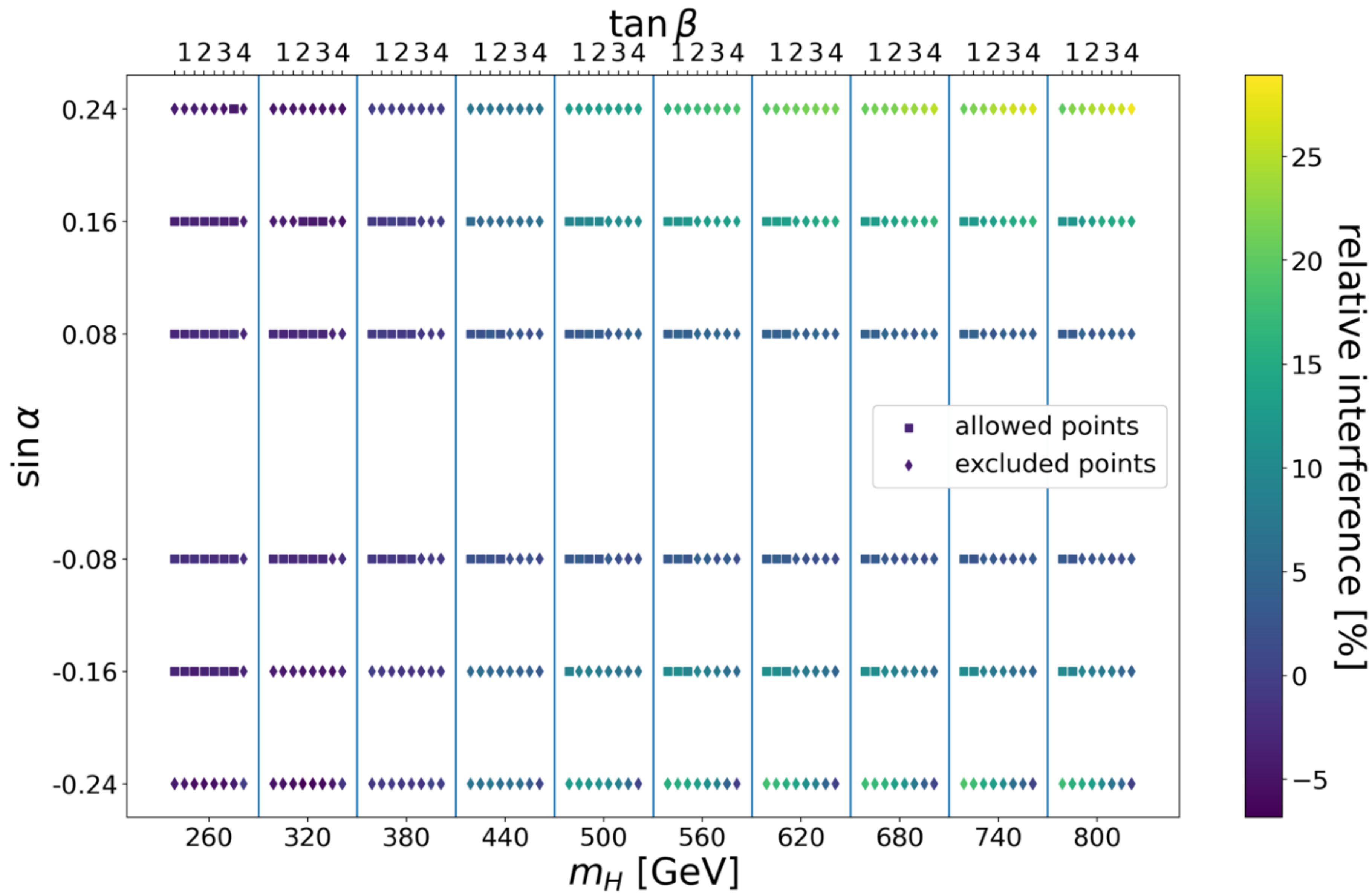
Benchmark	$\sin\alpha$	$\tan\beta$	m_H [GeV]	Γ_H [GeV]	$\kappa_{\lambda_{hhh}}$	σ [fb]	$\sigma_{\mathrm{S_H}}$ [fb]	Accessible in Run-3	Feature
BM1	0.16	1.0	620	4.6	0.96	50.5	13.5	✓	Max $(\Delta\sigma)_{\mathrm{rel}}$
BM2	0.16	0.5	440	1.5	0.96	91.6	56.4	✓	Max $(\Delta\sigma)^{\Sigma}_{\mathrm{rel}}$
BM3	0.16	0.5	380	0.8	0.96	119.8	90.1	✓	Max $(\Delta\sigma)^{\Sigma}_{\mathrm{rel}}$ 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 $\frac{\Gamma_H}{m_H}$

Today I will show this one

$$(\Delta\sigma)_{\mathrm{rel}} = \frac{\sigma_{\mathrm{total}} - \sigma_{\mathrm{res}} - \sigma_{\mathrm{non-res}}}{\sigma_{\mathrm{total}}}$$

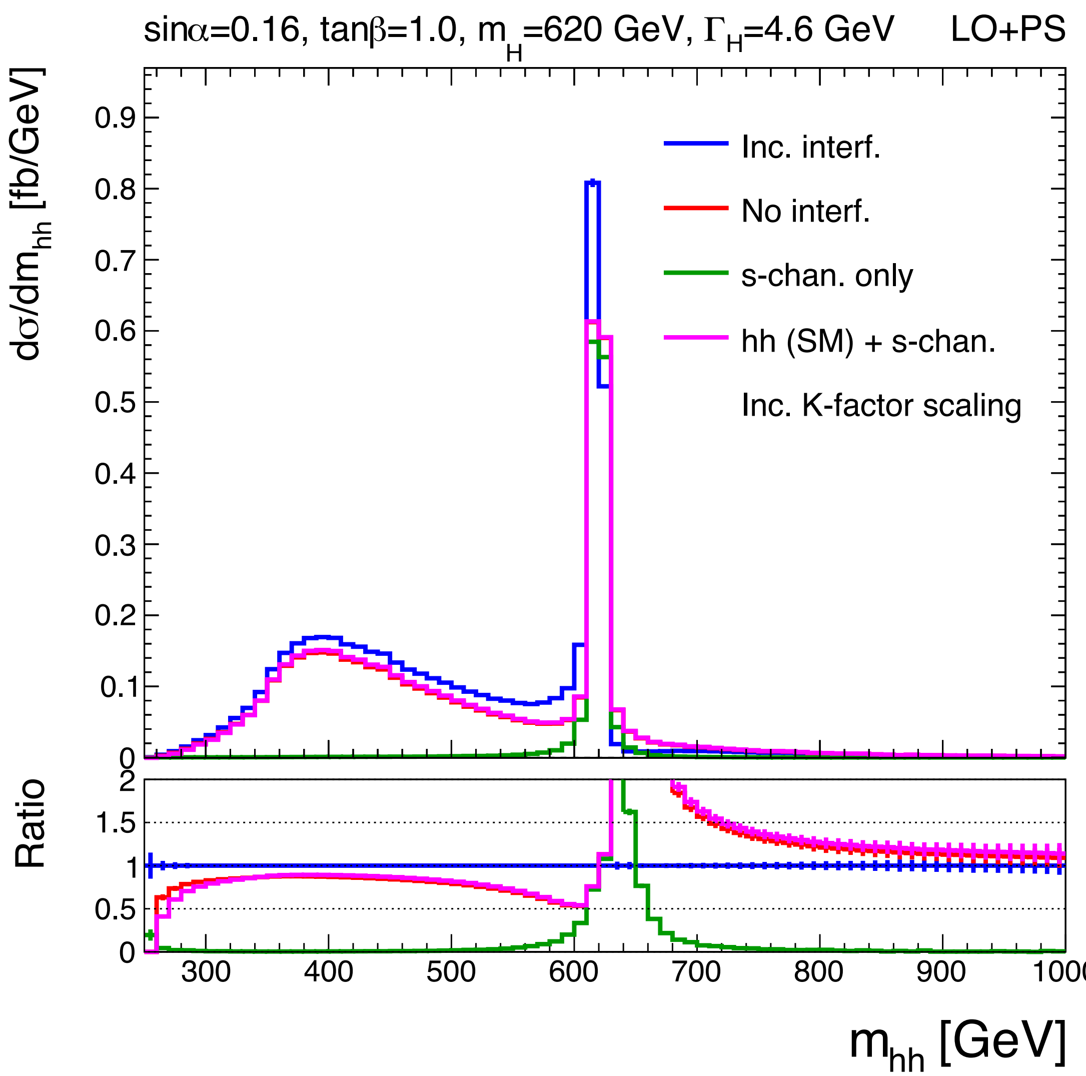
Parameter scans

- We perform scans to determine regions where the interference effect in the total cross-section is large
- Squares = allowed points, diamonds are excluded

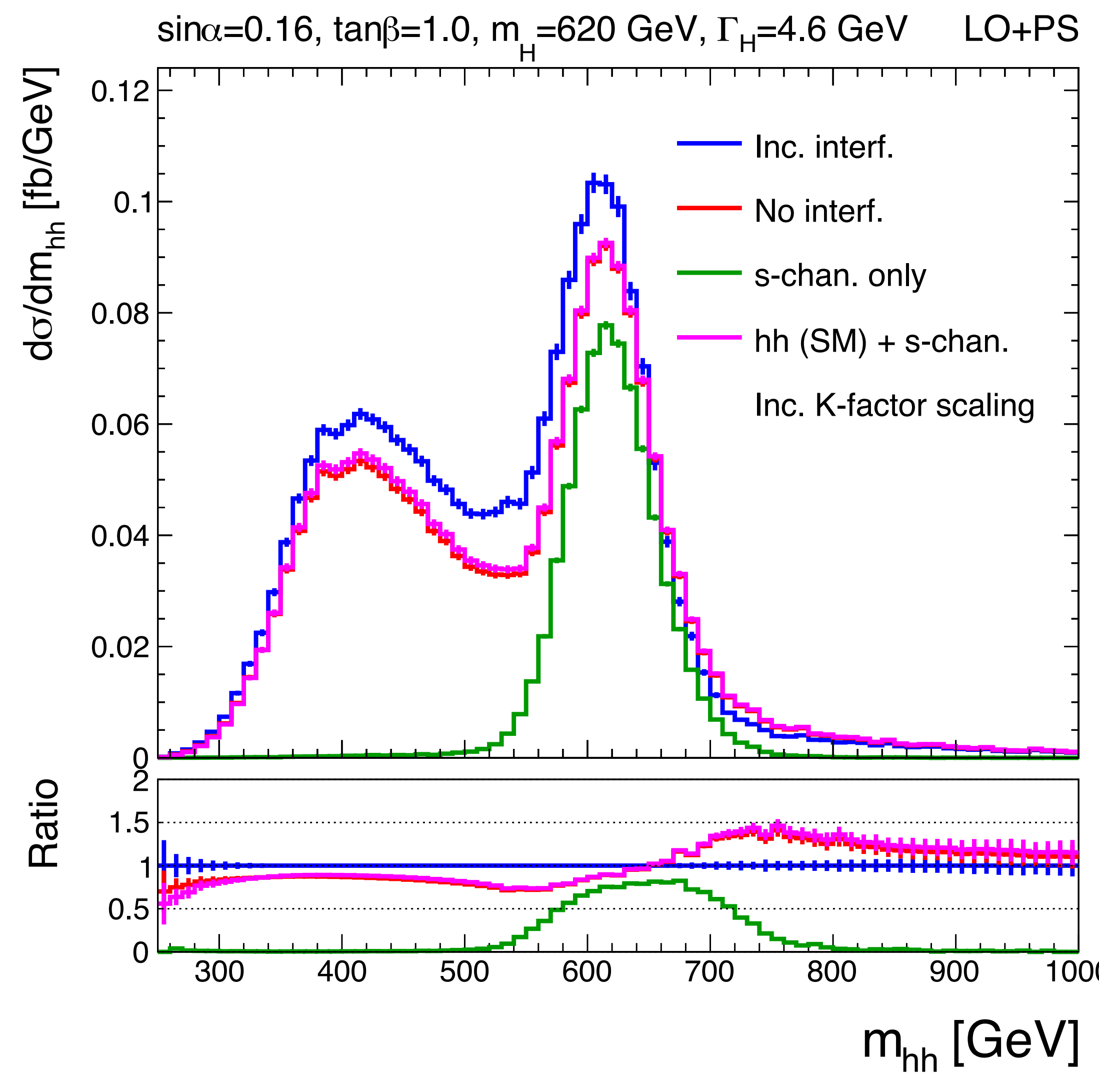


Benchmark distributions (BM1)

- di-Higgs mass distributions
- We show different assumptions for the modelling
  - Blue = full, correct description, Green = resonant-only (most CMS and ATLAS results so far), magenta = SM non-resonant + resonant with no interference (few analyses do this already)



Before smearing



HH→4b-like smearing

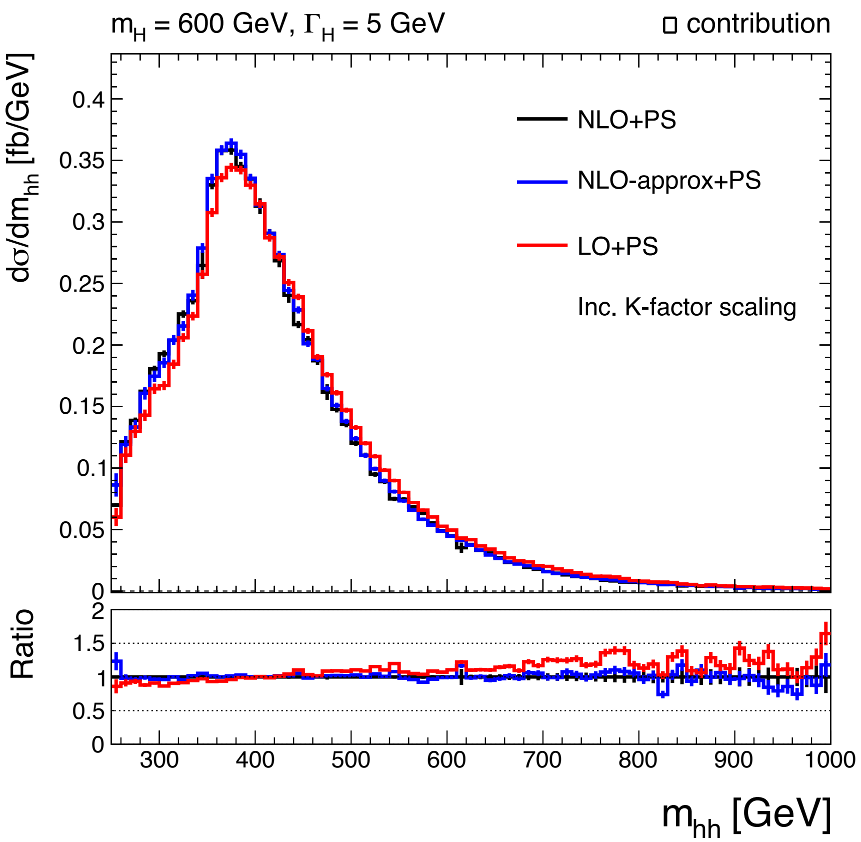
Conclusions

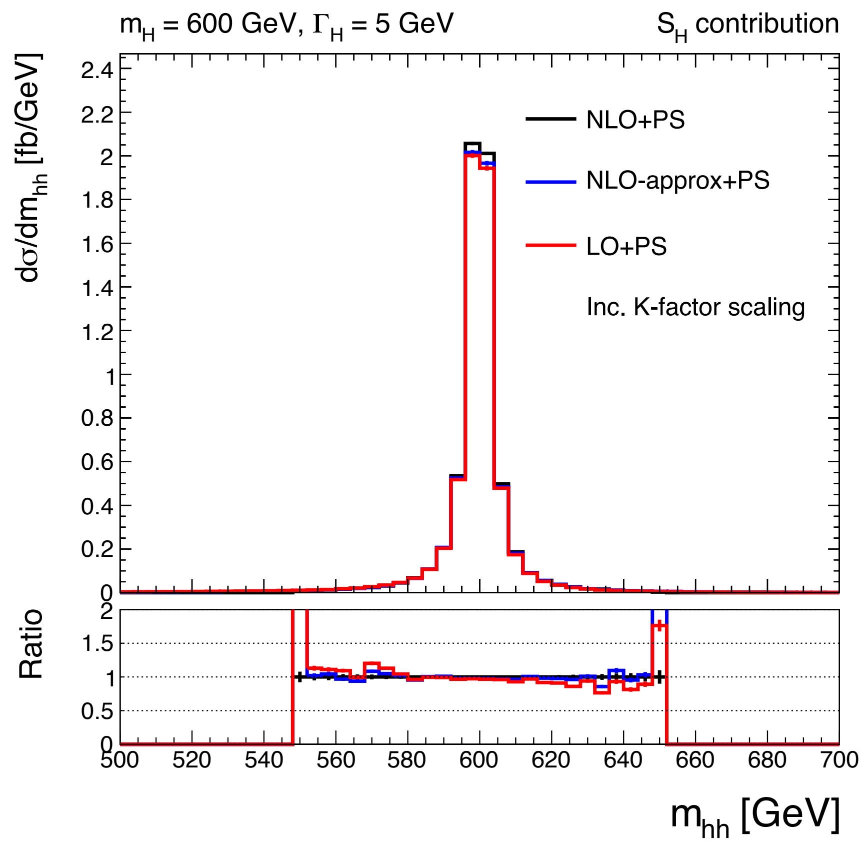
- Showed latest bounds on Higgs singlet model and investigated interference effects on cross-sections and distributions
- Interference effects are important for resonant di-Higgs searches
- Even without interference, the non-resonant contribution to the spectrum is sizeable and should be accounted for
- Martix element reweight tool developed to provide a convenient method for handling interference effects
  - Available on Gitlab: https://gitlab.com/danielwinterbottom/HHReweighter
- More details are provided in the publication: arXiv:2409.06651

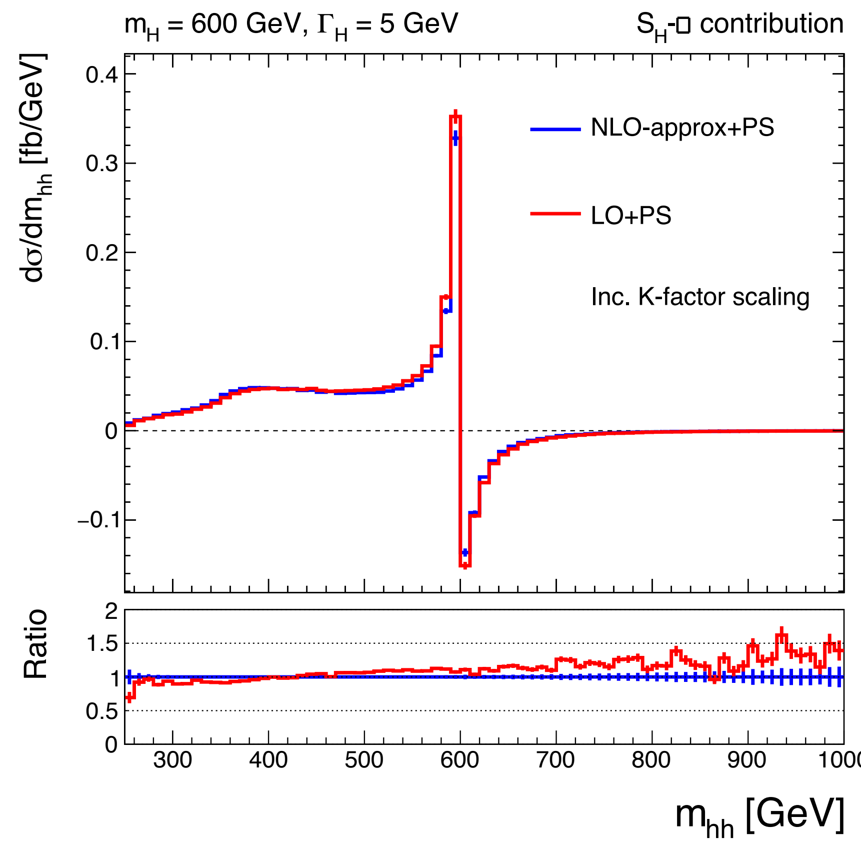
Backup

Including higher order corrections

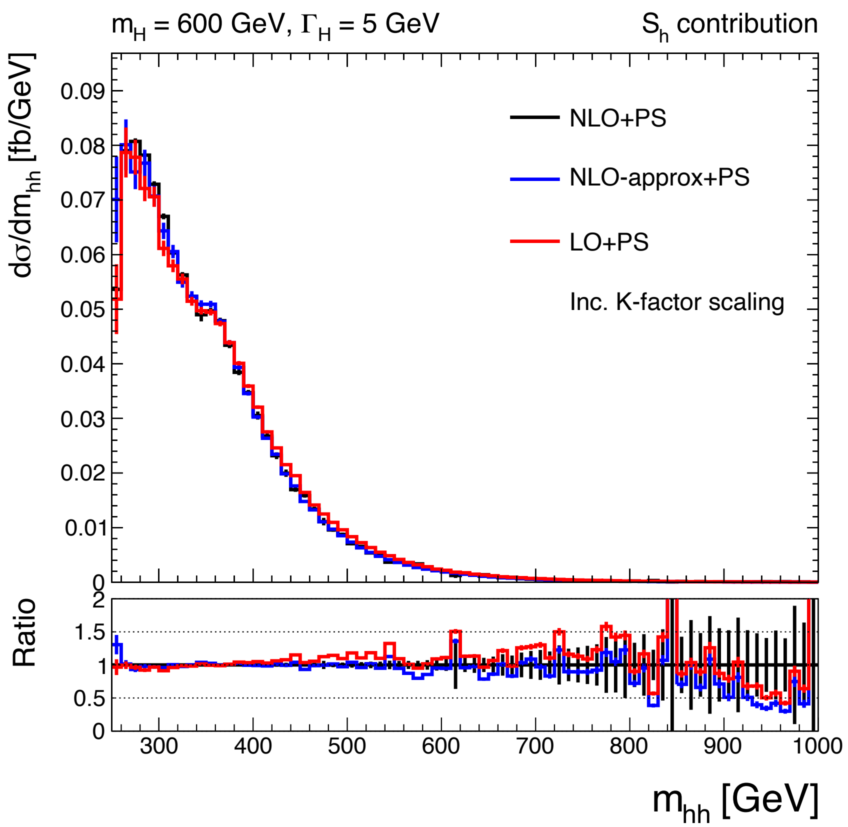
- Define approximate-method for reweighing NLO samples
    - Ignore additional radiation and compute MEs at LO
- NLO samples generated using POWHEG
    - No model currently available that can generate nonresonant+resonant di-Higgs with interference
    - We generate □, S_h, □ $- S_h$ for non-resonant, and S_H resonant samples and compare to reweighing where possible
    - We can also use reweighing to obtain approximate □ $- S_H$, and $S_H - S_h$ predictions - agree well with LO, to be checked once proper NLO MC is available

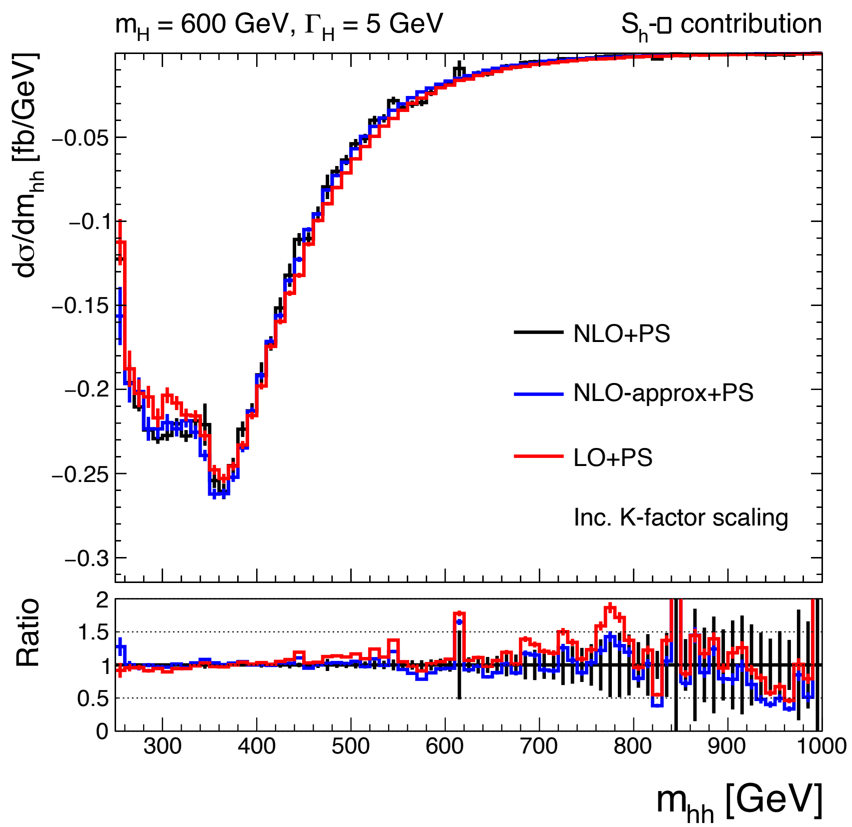


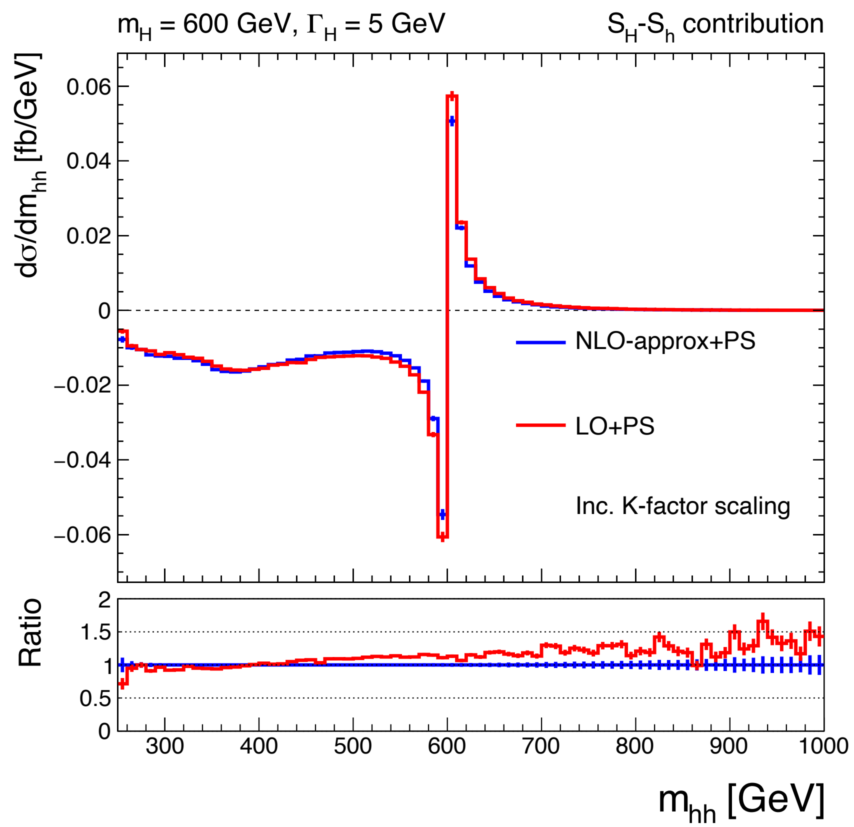




- Plots of di-Higgs mass for other terms

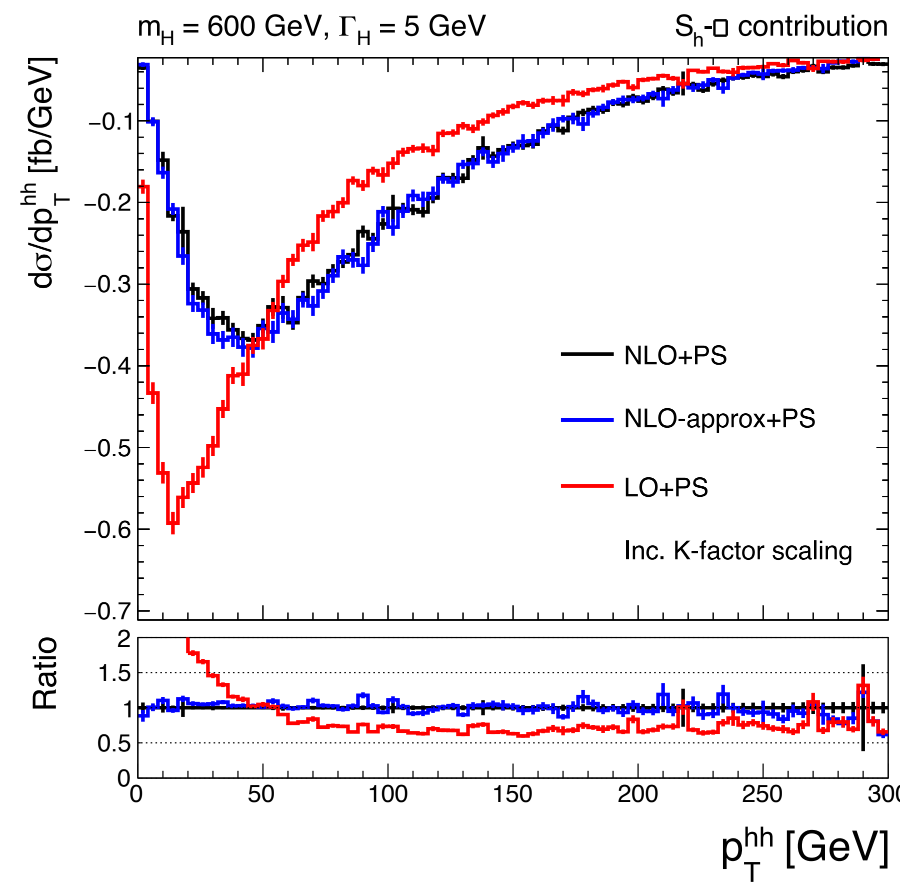


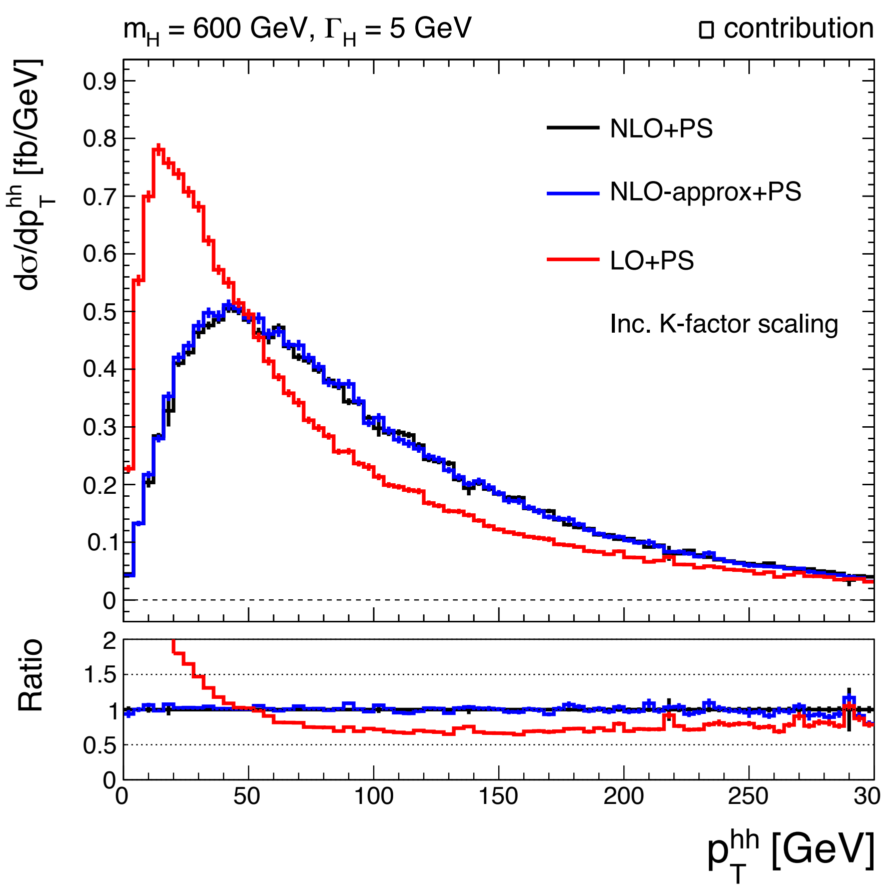


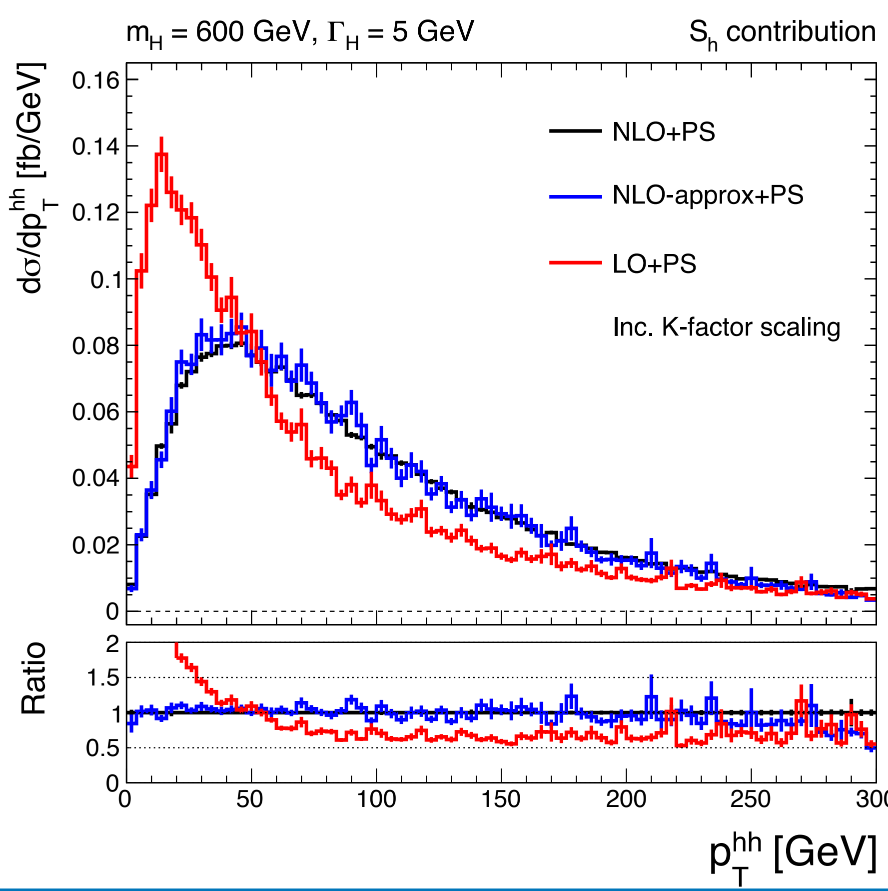


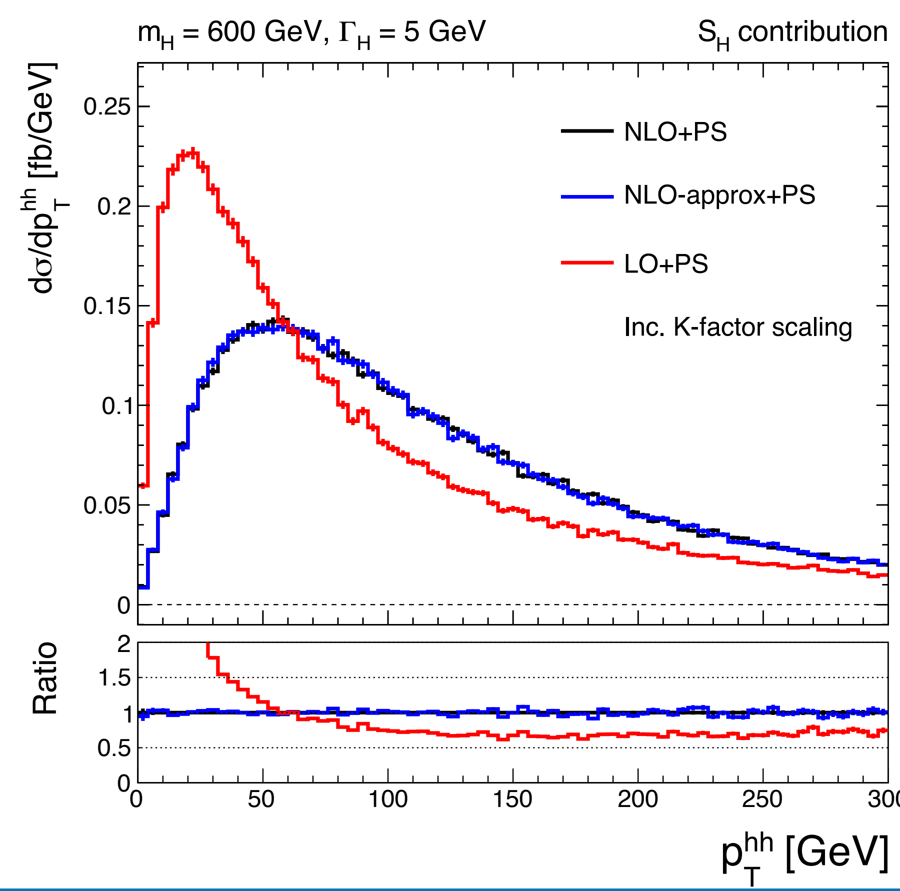
Additional plots of NLO validations

- Plots of di-Higgs p_T









More details on approximate NLO reweighting

When reweighting NLO samples we “ignore” the additional radiation if there is any as follows:

- We take the two outgoing h four-momenta from the ME and boost to the di-Higgs rest frame
- We then obtain the four-momenta for the incoming gluons by requiring both gluons to have zero transverse momentum, and equal and opposite longitudinal momentum, also requiring four-momentum conservation between incoming and outgoing particles
- When estimating the MEs we also average over all possible spin-states of the incoming gluons
- If there is no radiation, then we compute ME in the usual way as if the event is from a LO generator

Couplings / Width

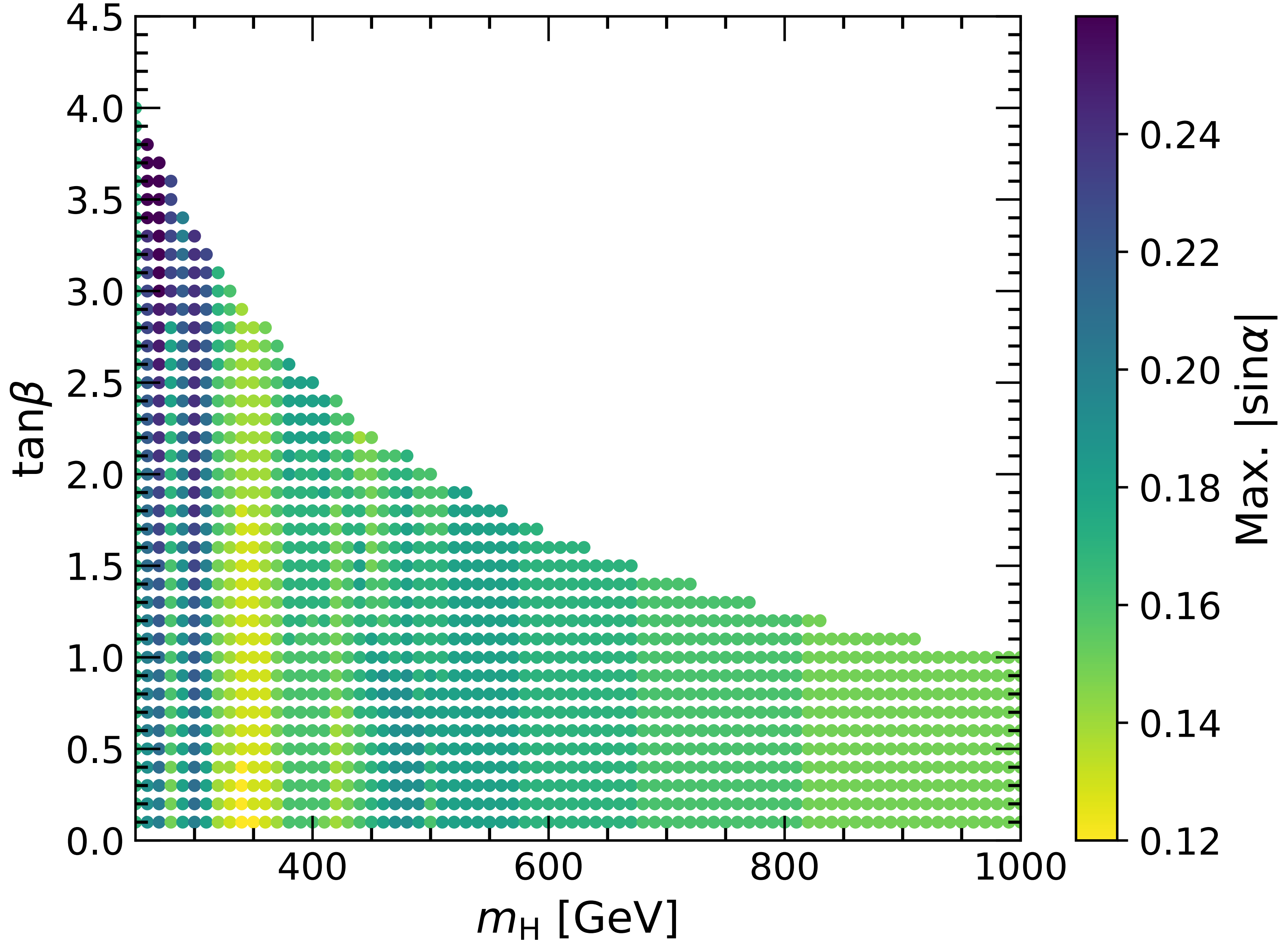
- Coupling modifiers (wrt SM couplings) in the singlet model

$$
\begin{aligned}
\kappa^{h}_{f/V} &= \cos\alpha, \\
\kappa^{H}_{f/V} &= \sin\alpha, \\
\kappa_{\lambda_{hhh}} &= \cos^3\alpha - \tan\beta\sin^3\alpha, \\
\kappa_{\lambda_{Hhh}} &= \frac{2m_h^2 + m_H^2}{m_h^2}\,\frac{\sin(2\alpha)}{2}(\cos\alpha + \tan\beta\sin\alpha),
\end{aligned}
$$

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

Allowed points

- Allowed points in tanβ-m_H plane



Smearing

- Assume HH→4b like smearing by the CMS detector

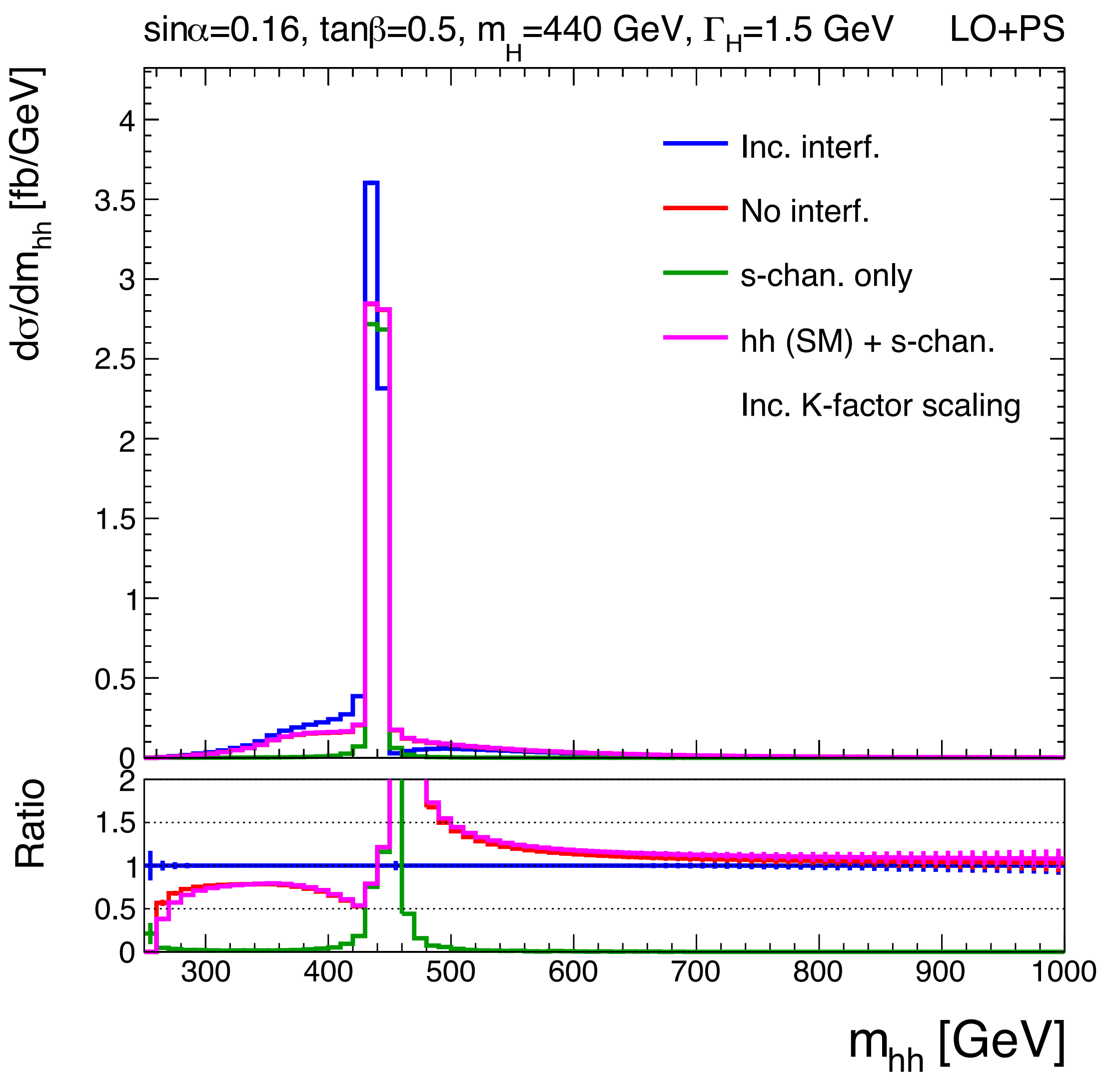
- Angular smearing: smear ϕ and η by randomly sampling a Gaussian with mean=0 and σ=0.05

- Energy: smear energies by randomly sampling a Gaussian with mean=0 and σ=0.15 - this is to match the Higgs mass resolutions quoted in arXiv:1912.06046

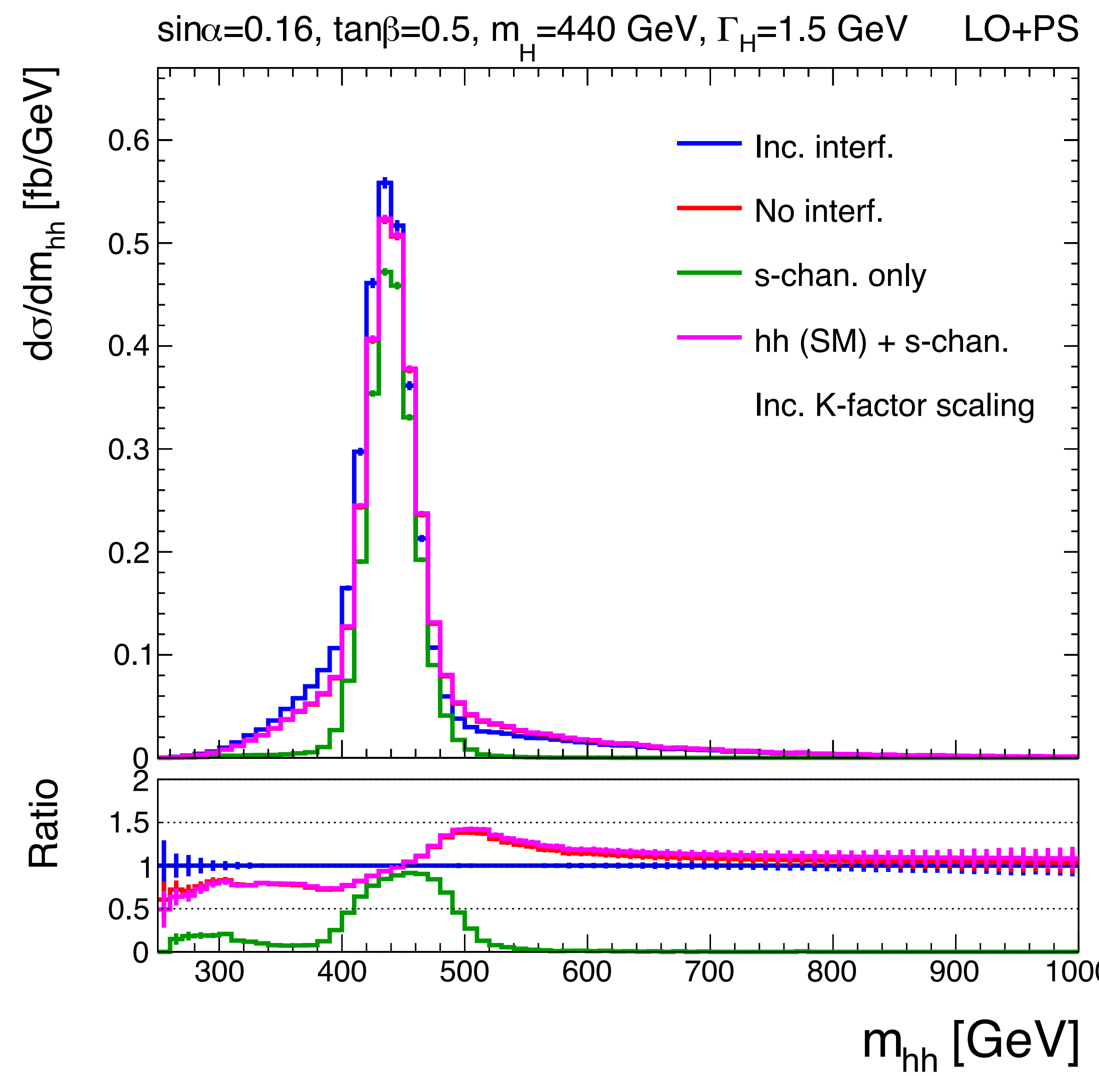
- Additional cuts to match CMS Run-3 trigger requirements: b-jet p_T > 30 GeV, b-jet $|\eta|<2.5$, and H_T > 280 GeV (https://cds.cern.ch/record/2868787)

Benchmark distributions (BM2)

- di-Higgs mass distributions
- We show different assumptions for the modelling
  - Blue = full, correct description, Green = resonant-only (most CMS and ATLAS results so far), magenta = SM non-resonant + resonant with no interference (few analyses do this already)



Before smearing



HH→4b-like smearing

Benchmark distributions (BM3)

- di-Higgs mass distributions
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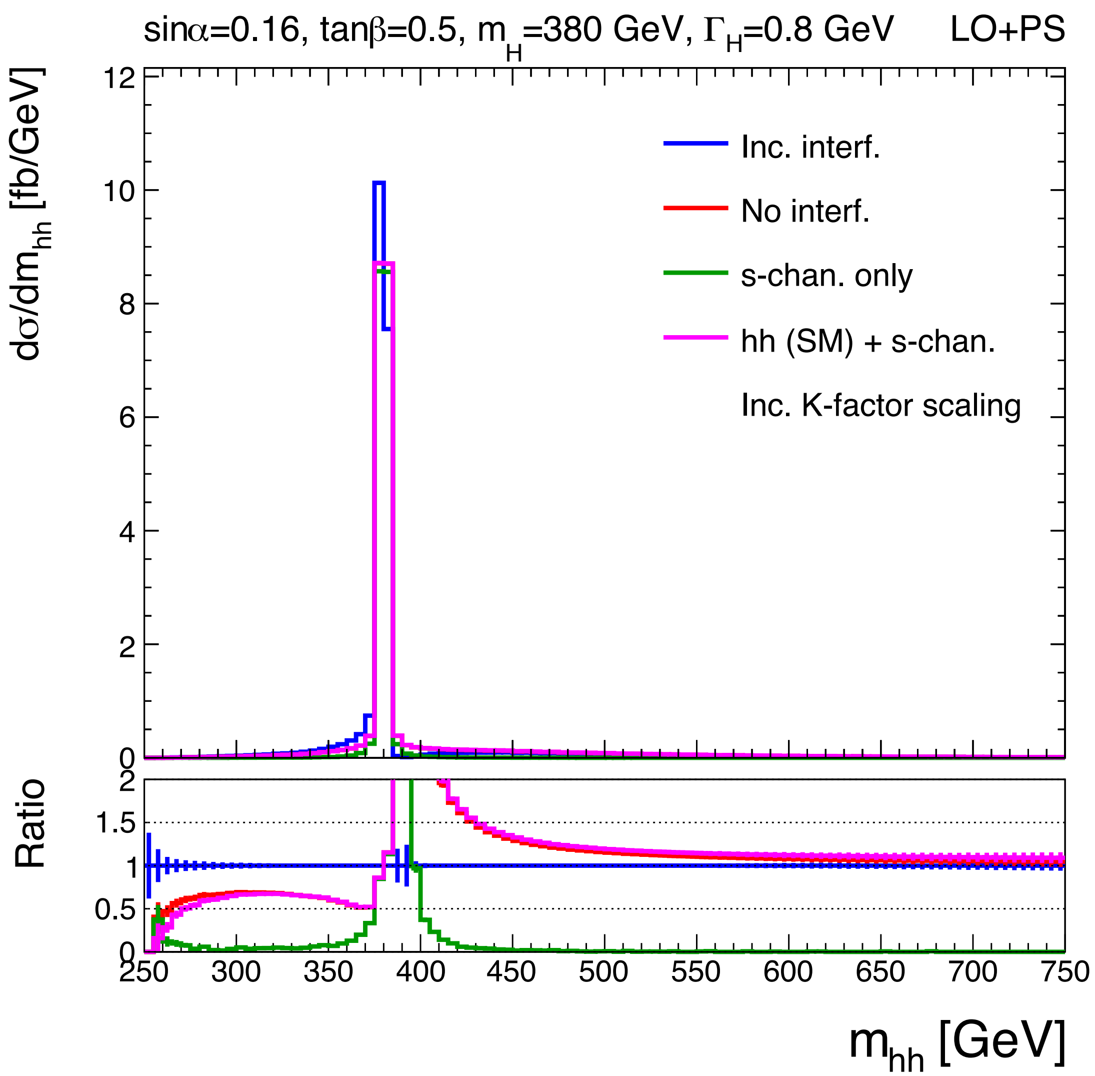
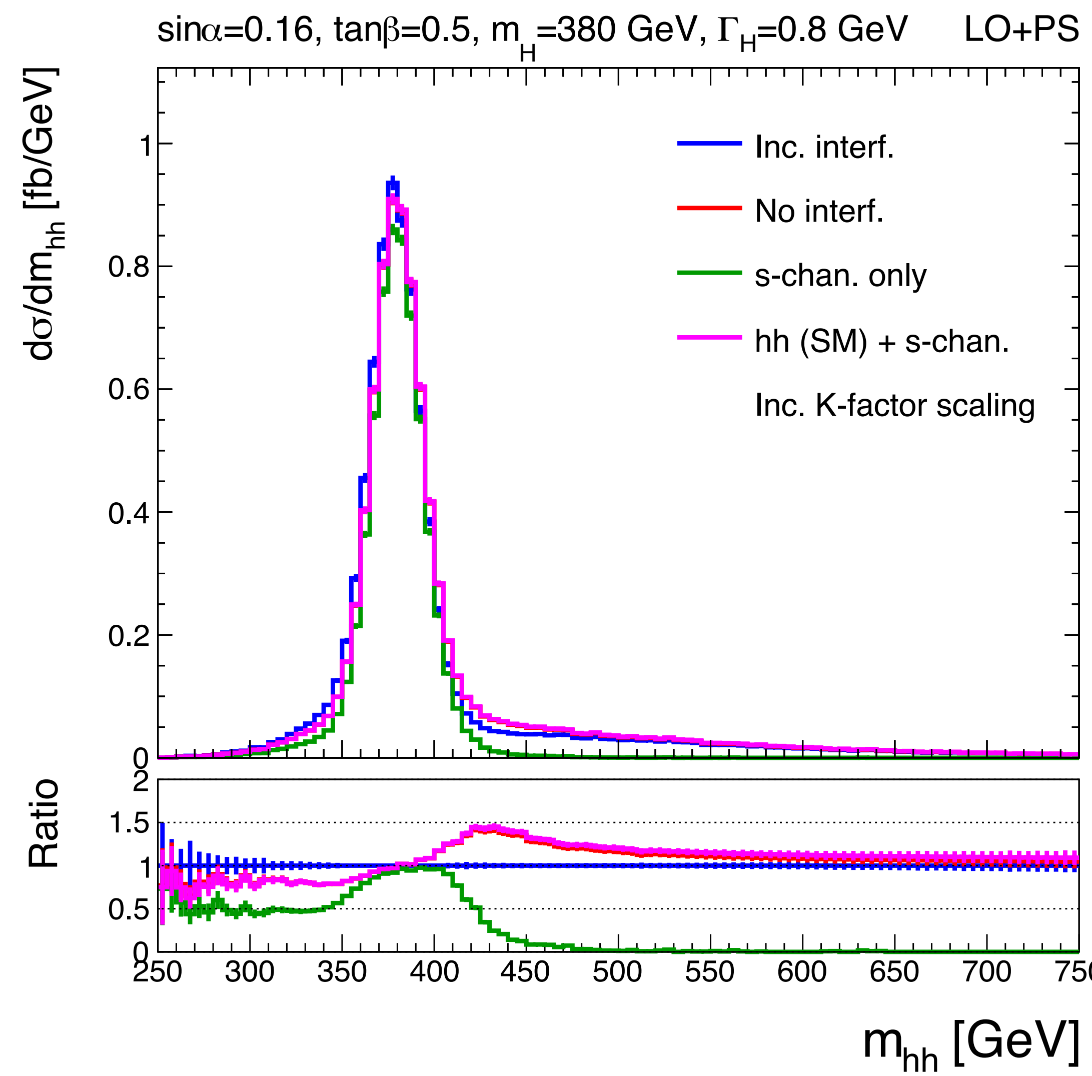


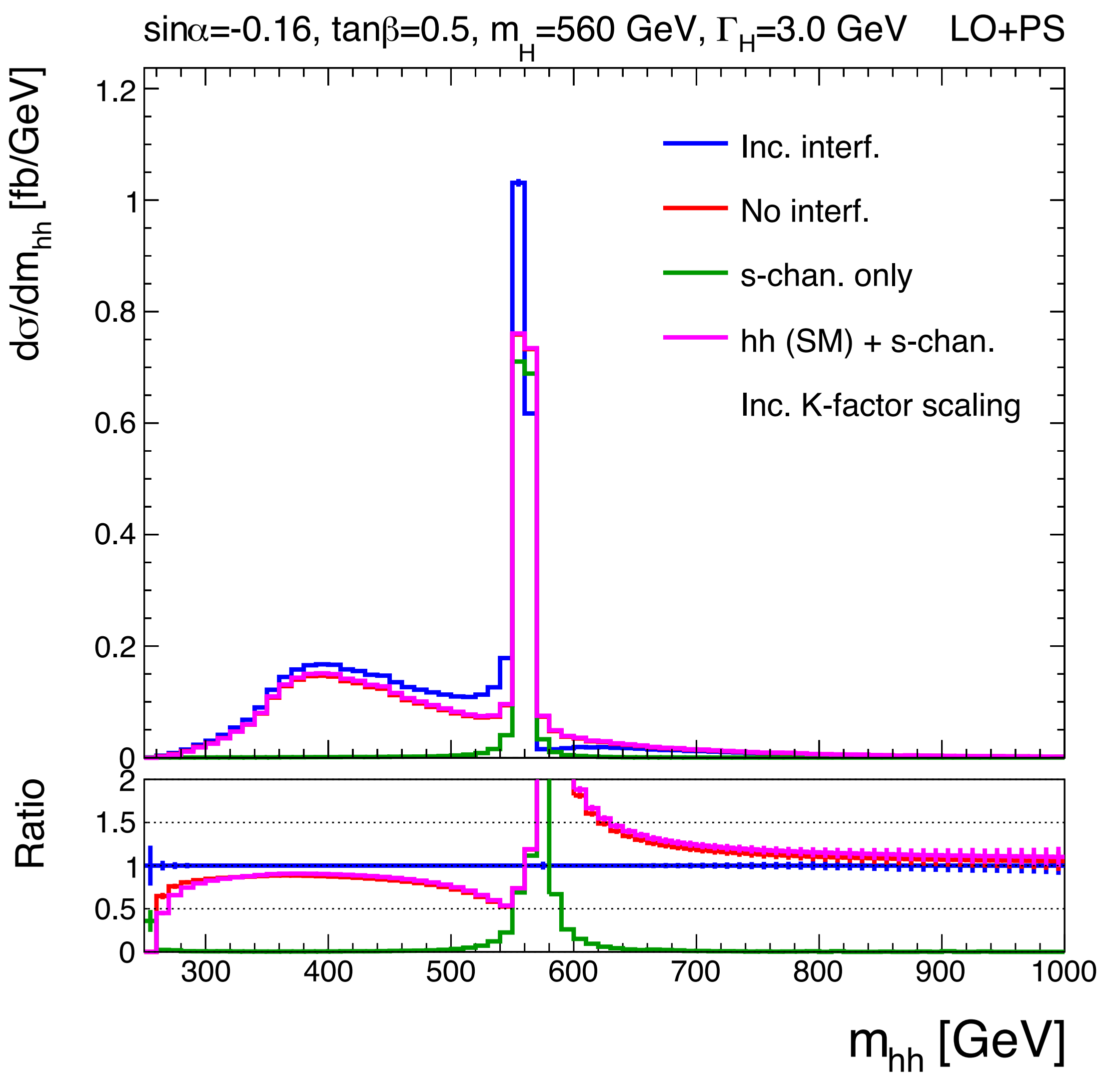
Before smearing



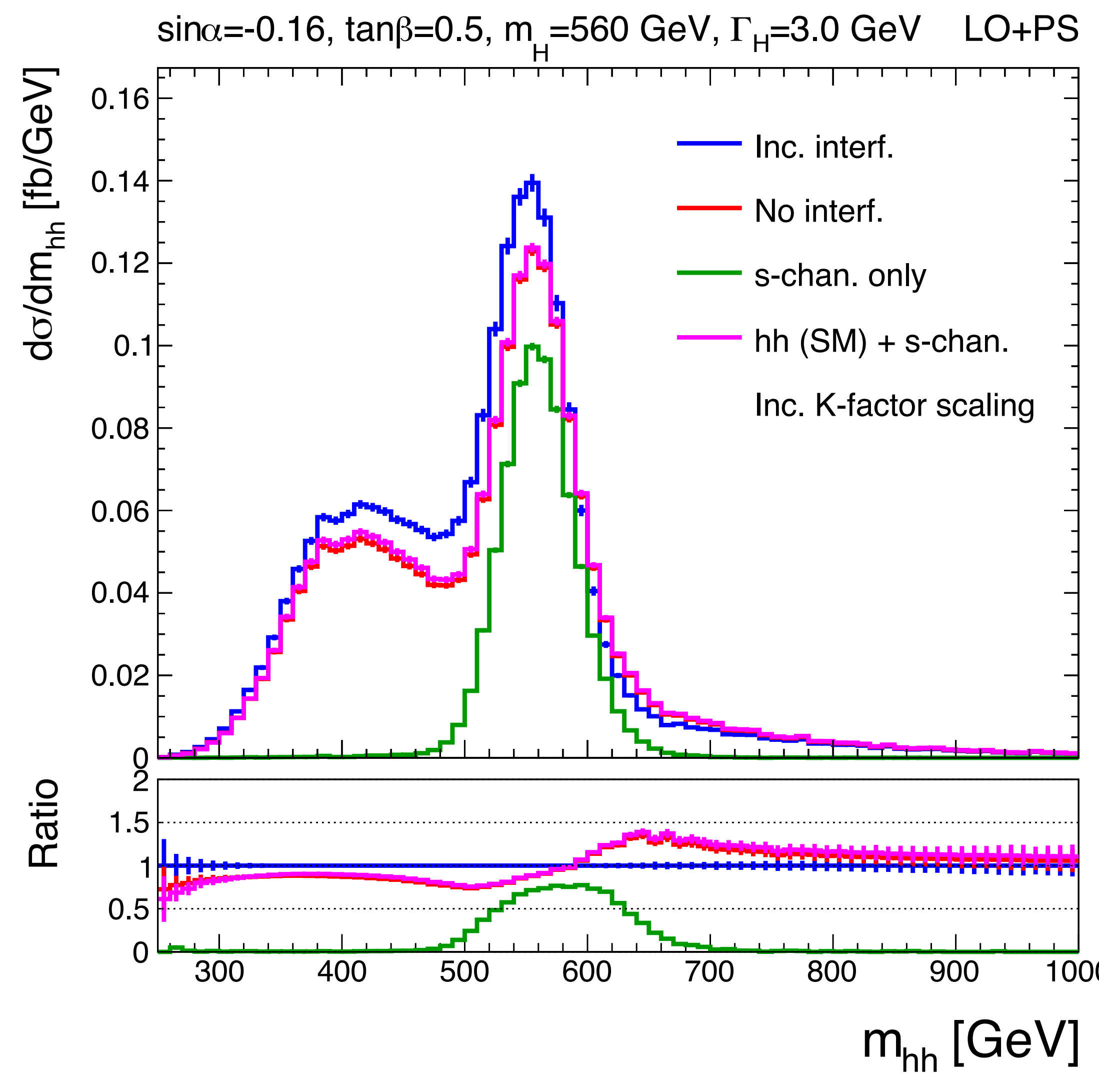
HH→4b-like smearing

Benchmark distributions (BM4)

- di-Higgs mass distributions
- We show different assumptions for the modelling
  - Blue = full, correct description, Green = resonant-only (most CMS and ATLAS results so far), magenta = SM non-resonant + resonant with no interference (few analyses do this already)



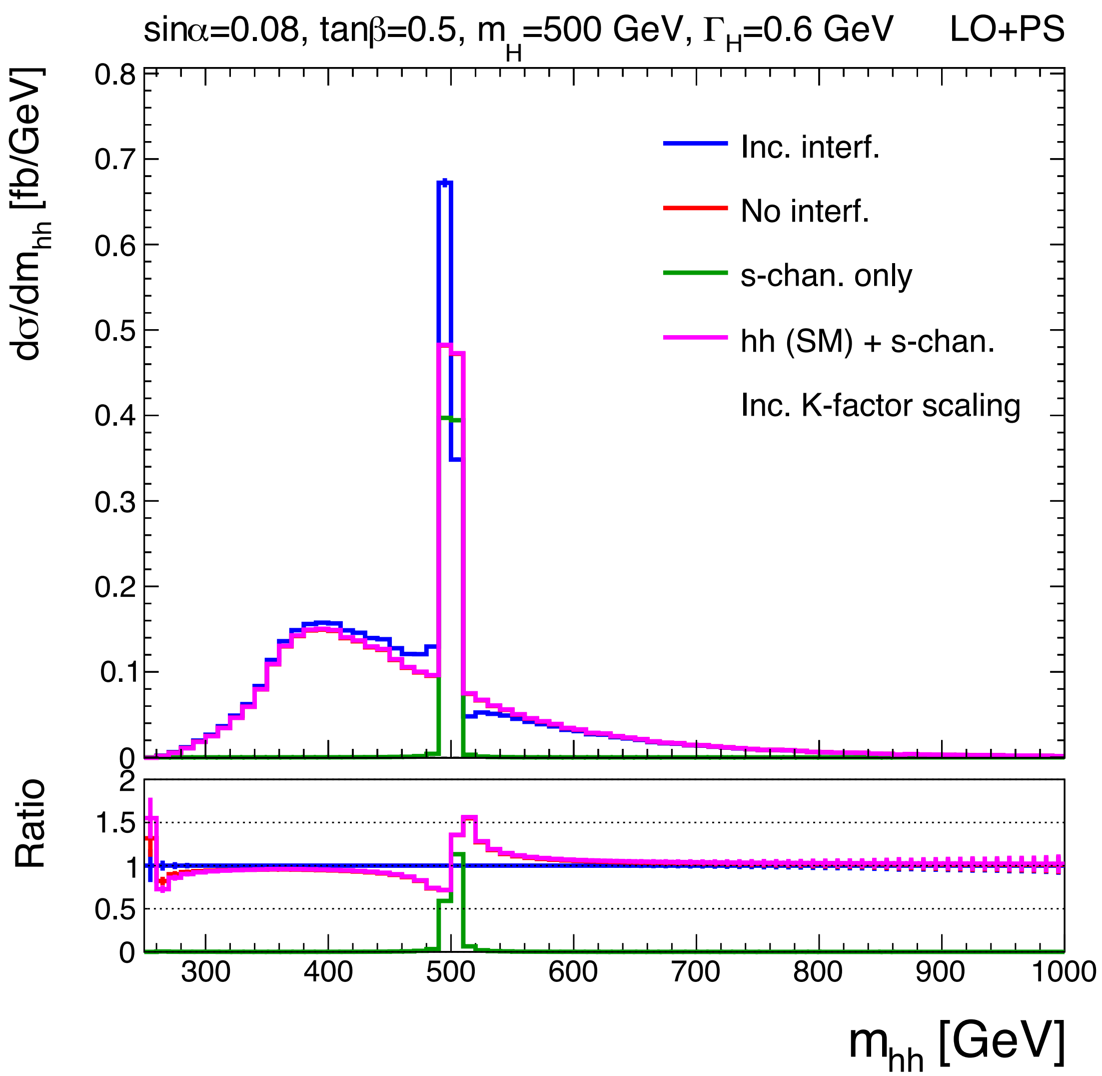
Before smearing



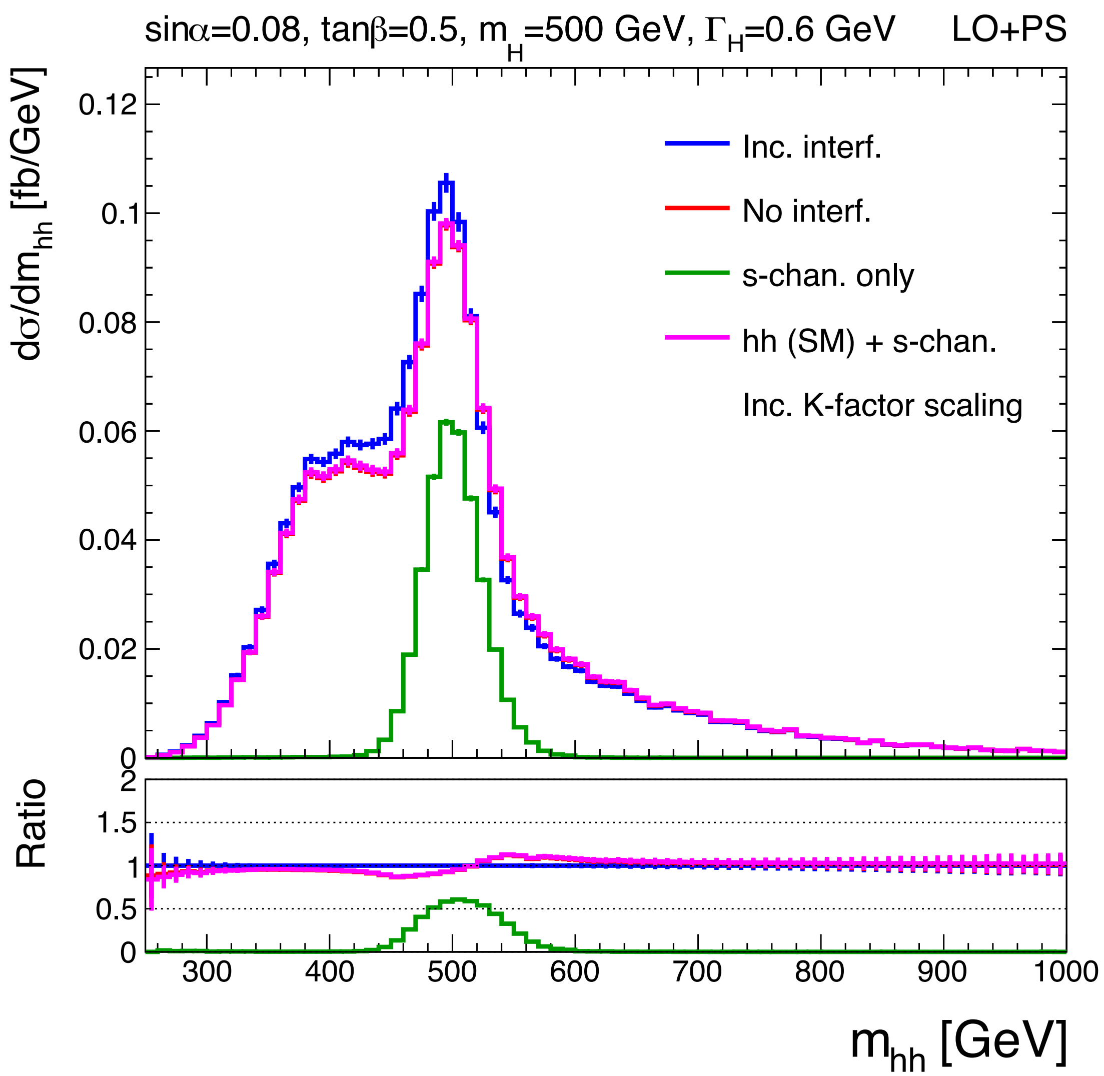
HH→4b-like smearing

Benchmark distributions (BM5)

- di-Higgs mass distributions
- We show different assumptions for the modelling
  - Blue = full, correct description, Green = resonant-only (most CMS and ATLAS results so far), magenta = SM non-resonant + resonant with no interference (few analyses do this already)



Before smearing



HH→4b-like smearing

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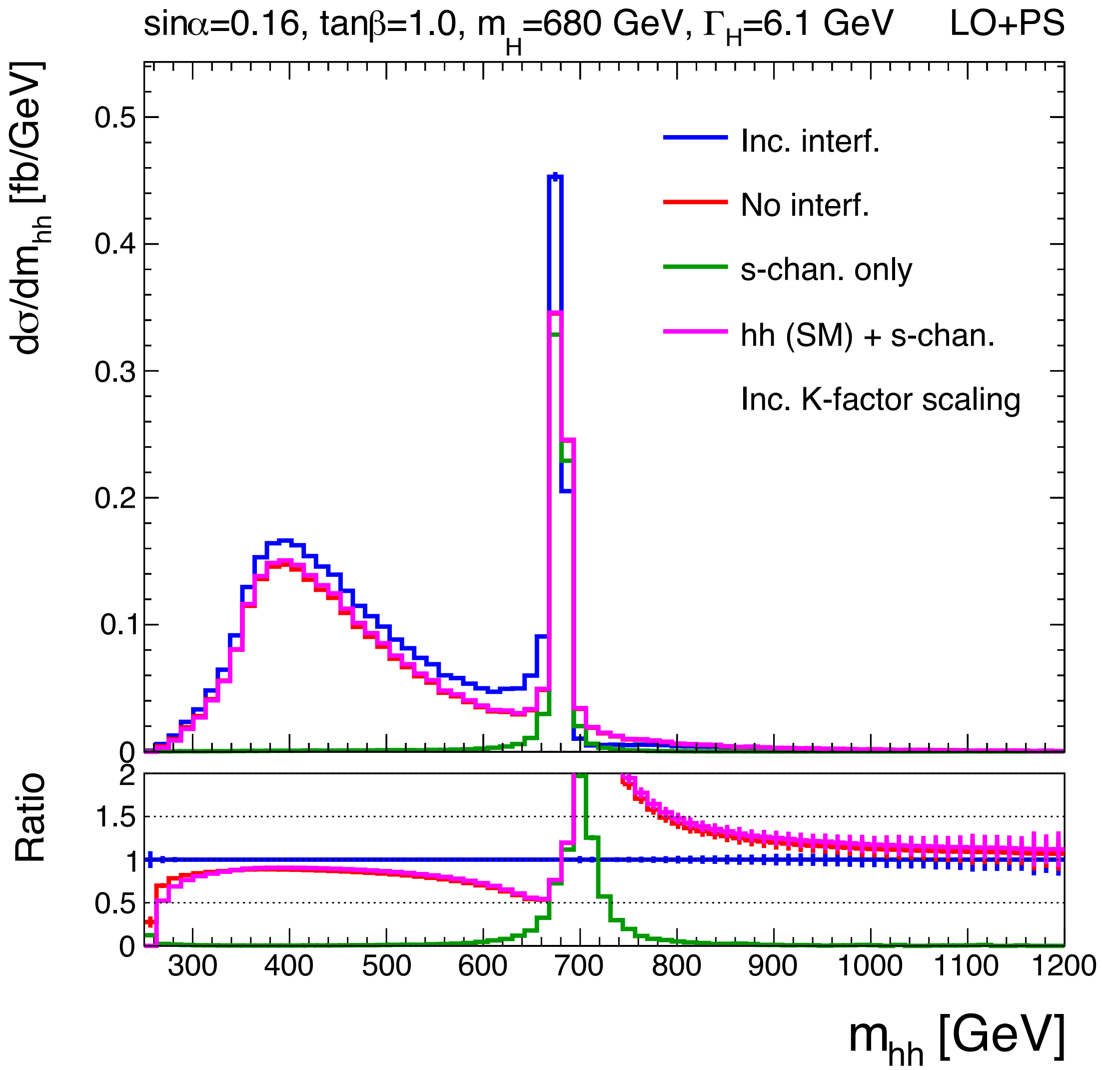
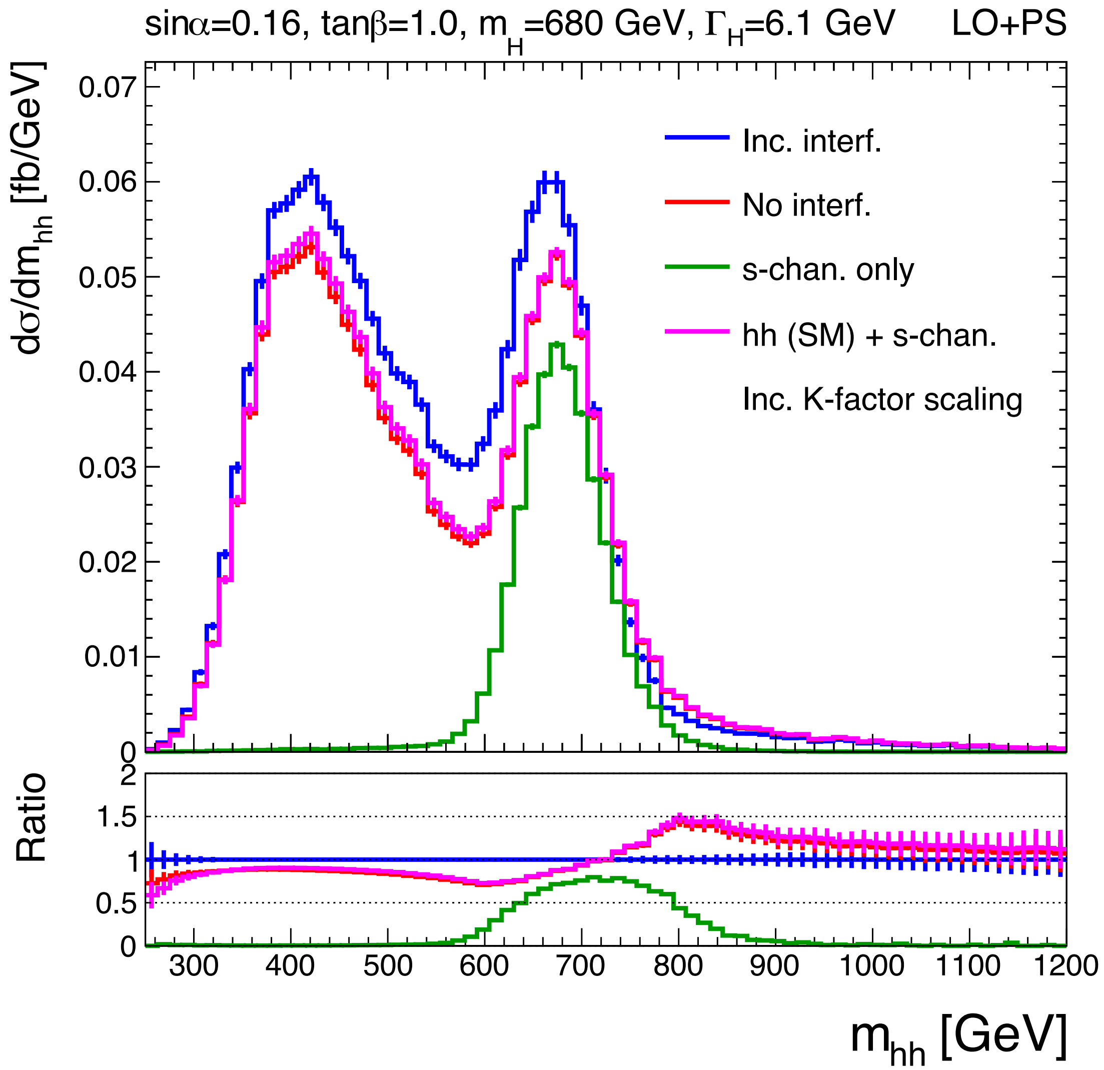


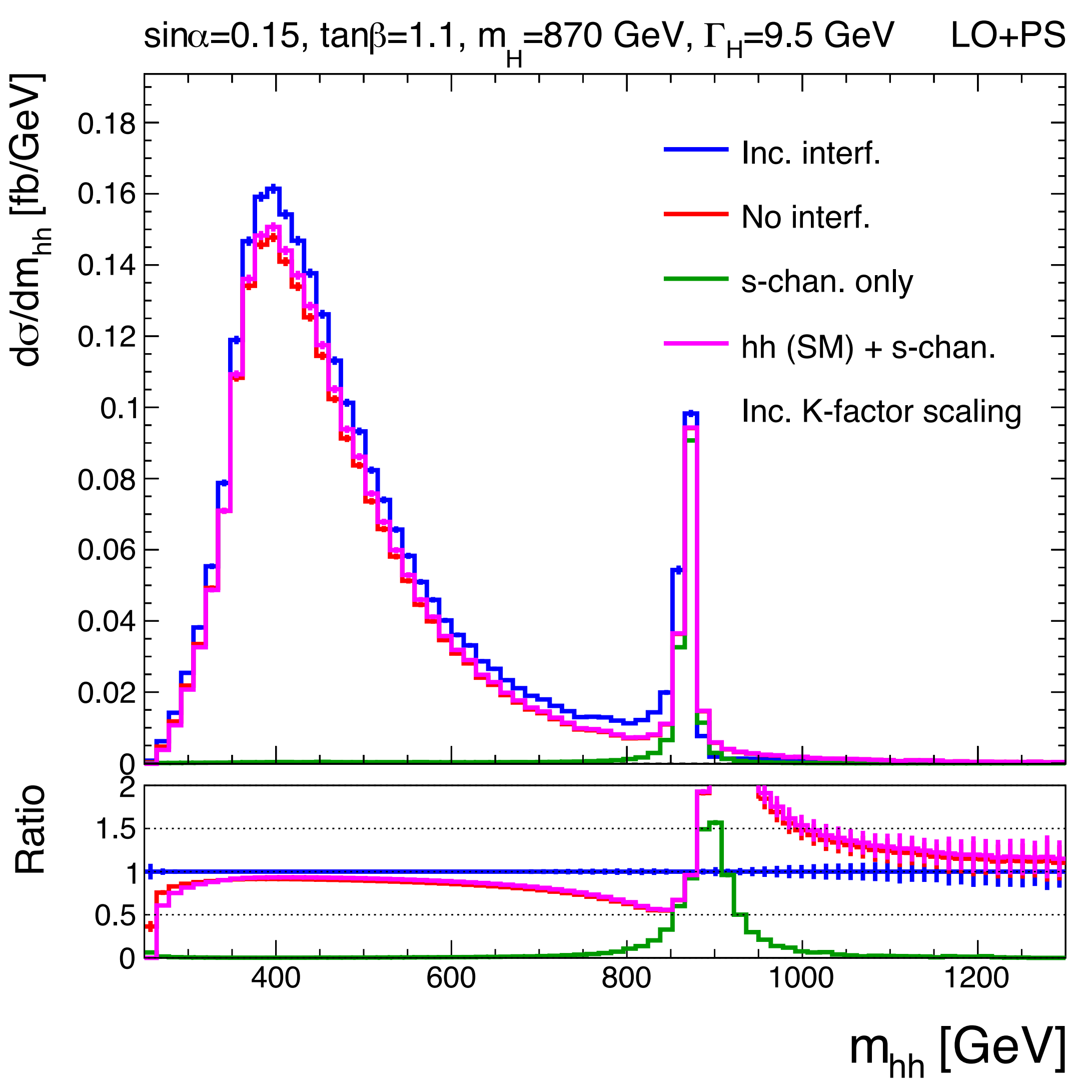
Before smearing



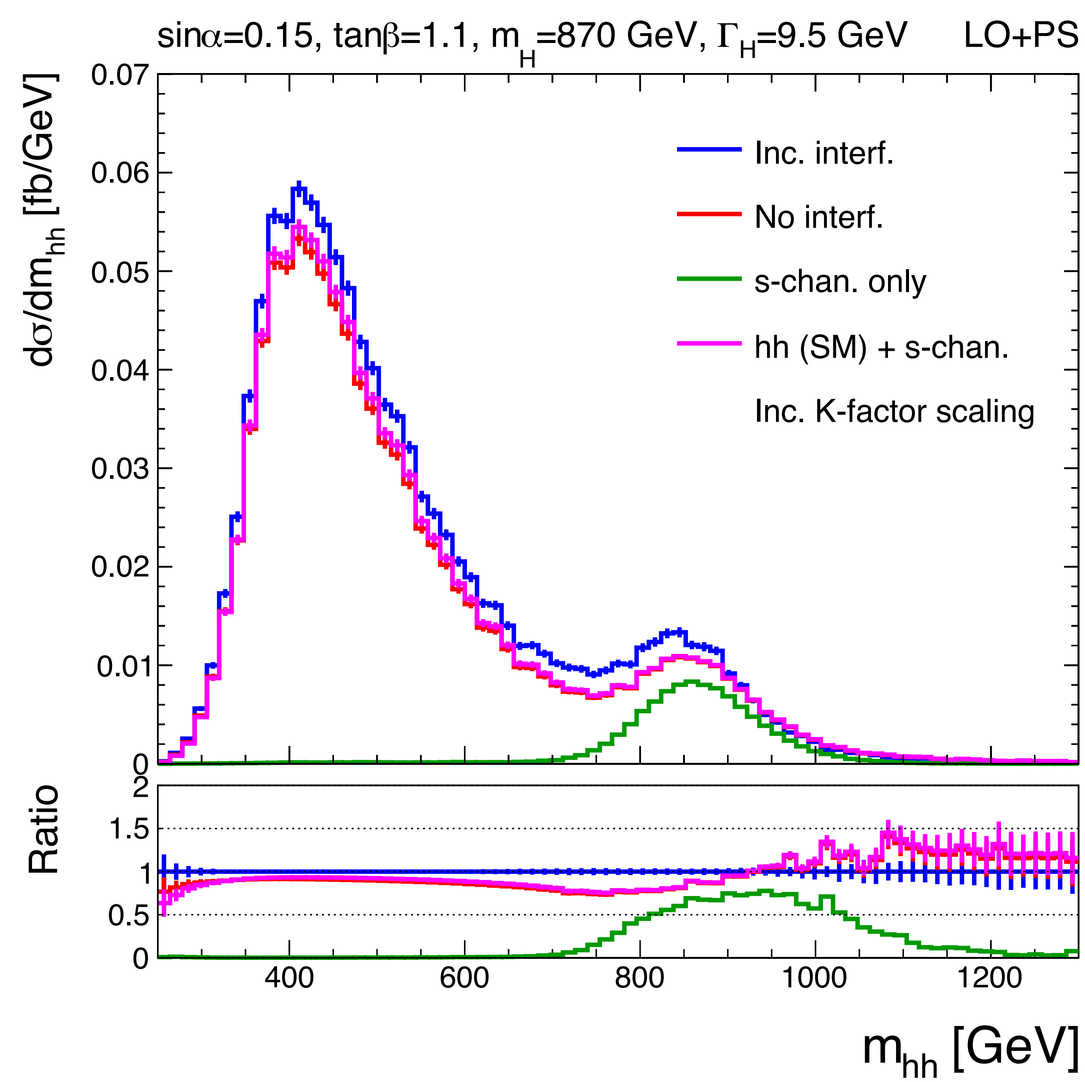
HH→4b-like smearing

Benchmark distributions (BM7)

- di-Higgs mass distributions
- We show different assumptions for the modelling
  - Blue = full, correct description, Green = resonant-only (most CMS and ATLAS results so far), magenta = SM non-resonant + resonant with no interference (few analyses do this already)



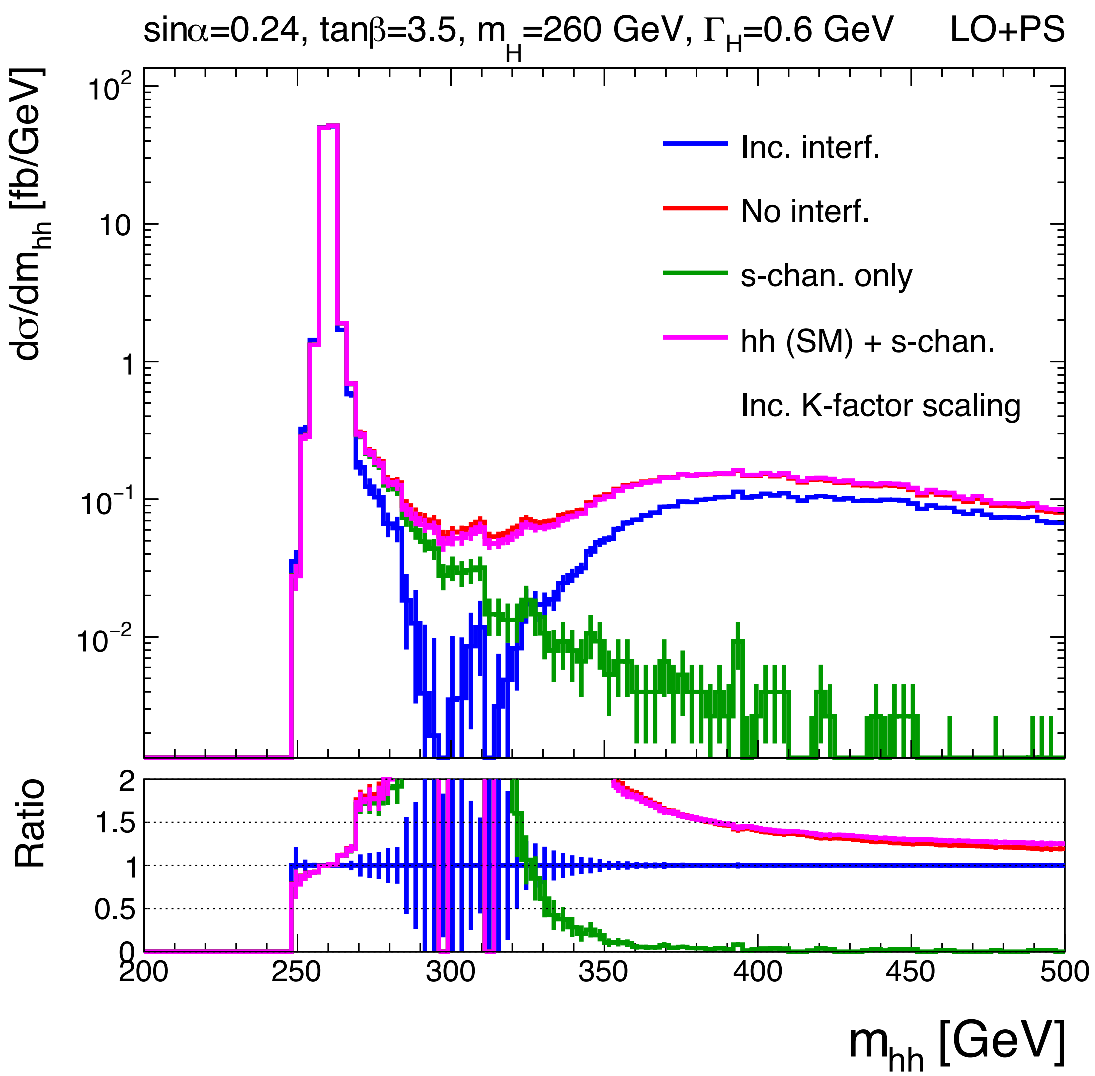
Before smearing



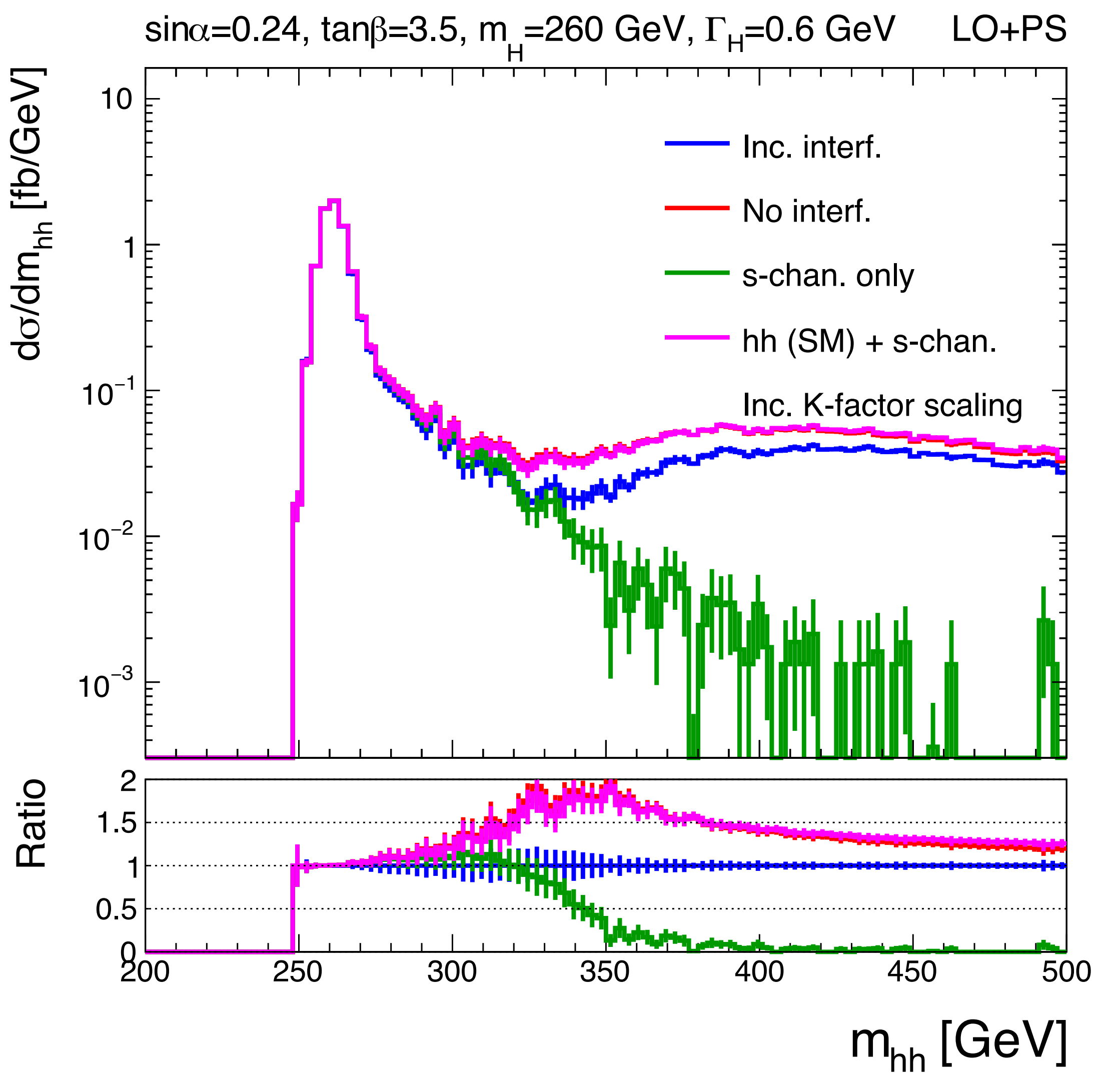
HH→4b-like smearing

Benchmark distributions (BM8)

- di-Higgs mass distributions
- We show different assumptions for the modelling
  - Blue = full, correct description, Green = resonant-only (most CMS and ATLAS results so far), magenta = SM non-resonant + resonant with no interference (few analyses do this already)



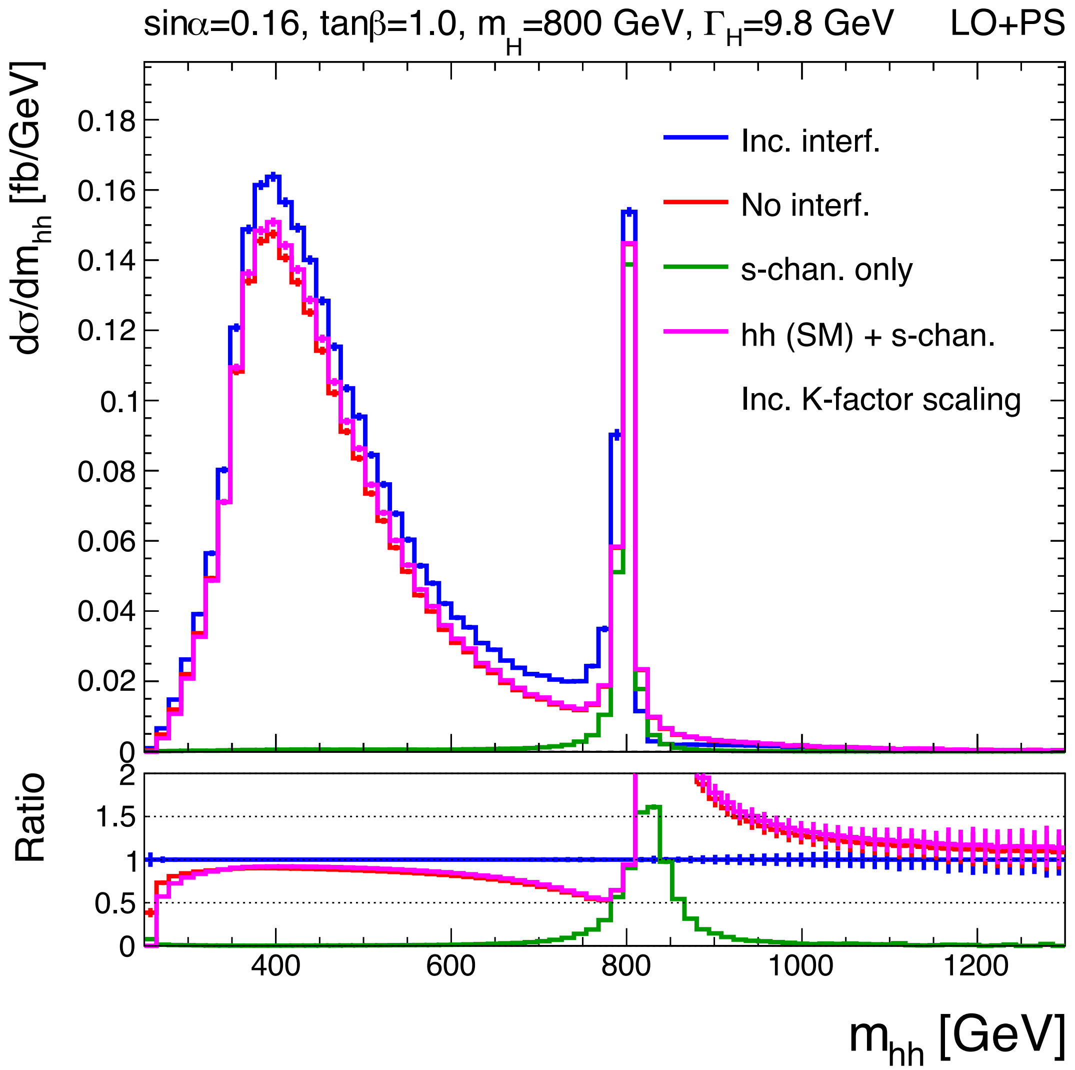
Before smearing



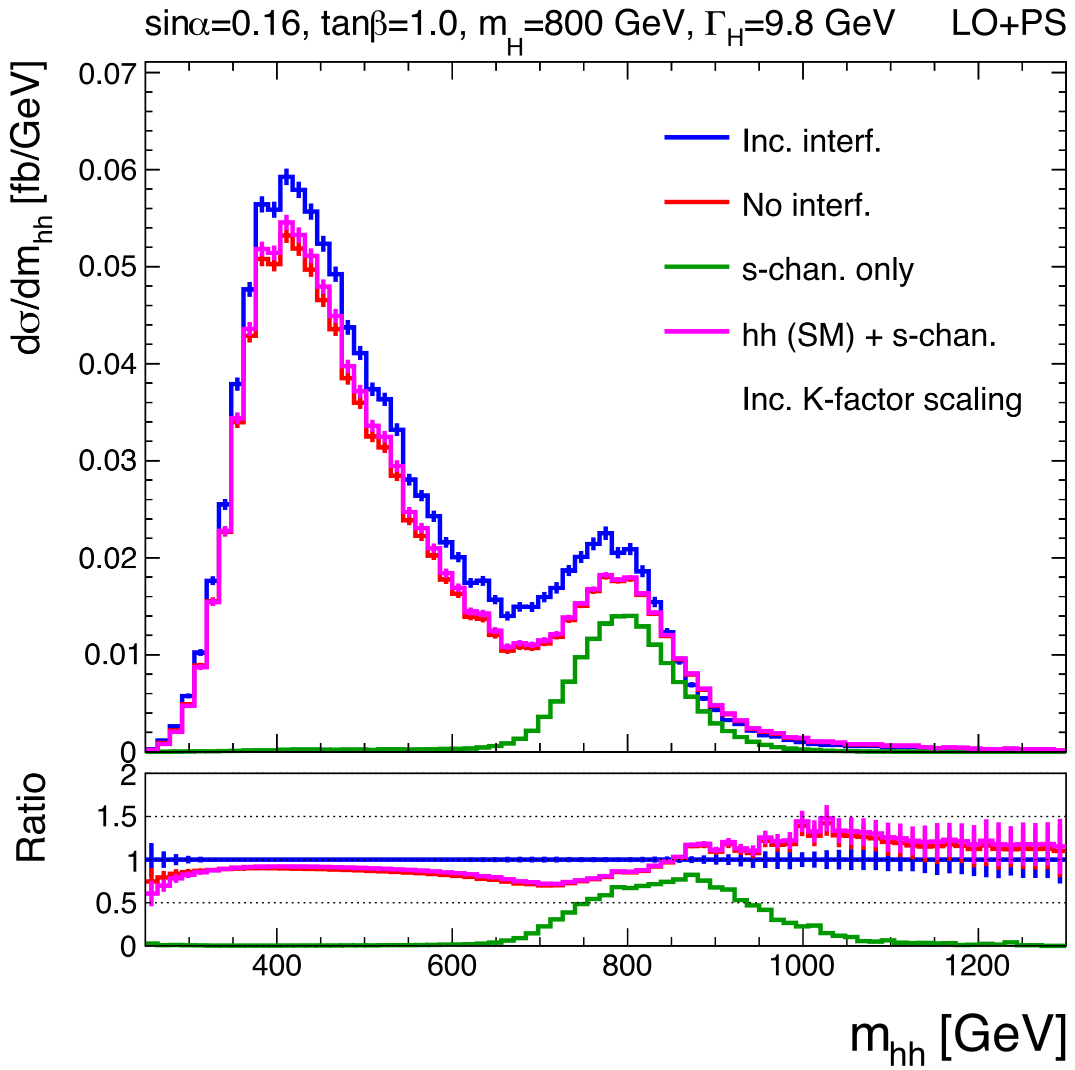
HH→4b-like smearing

Benchmark distributions (BM9)

- di-Higgs mass distributions
- We show different assumptions for the modelling
  - Blue = full, correct description, Green = resonant-only (most CMS and ATLAS results so far), magenta = SM non-resonant + resonant with no interference (few analyses do this already)



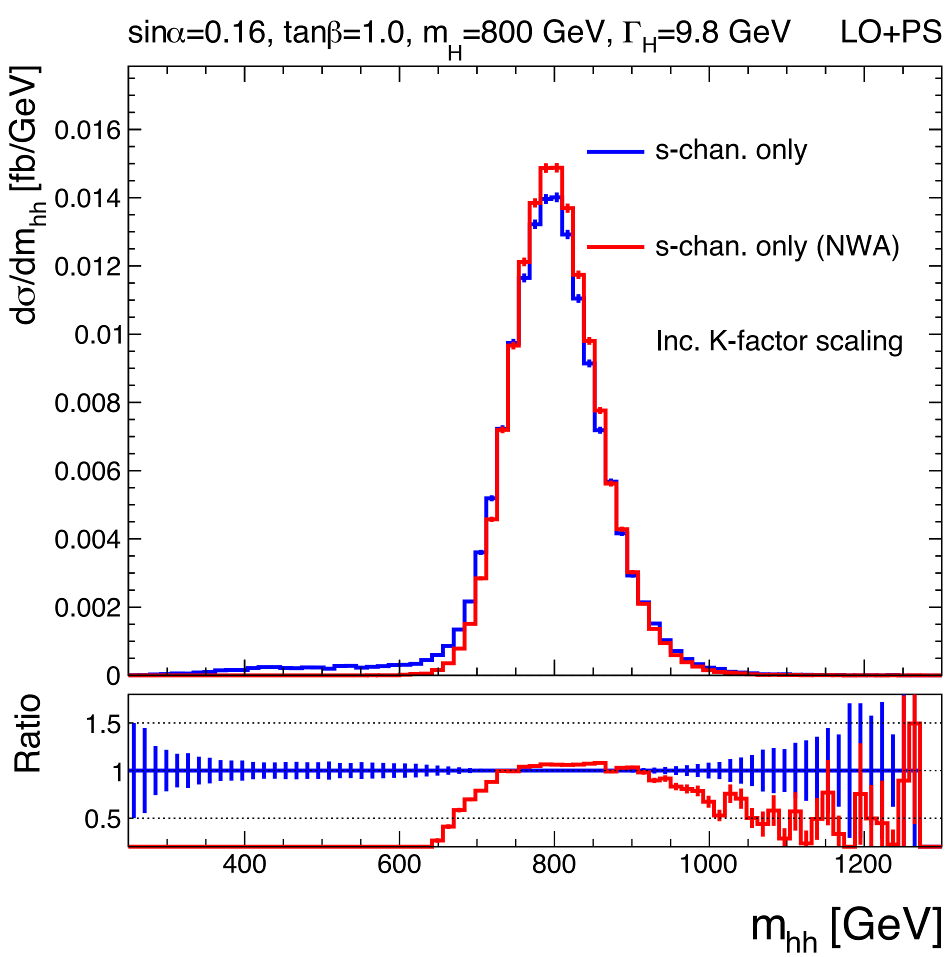
Before smearing

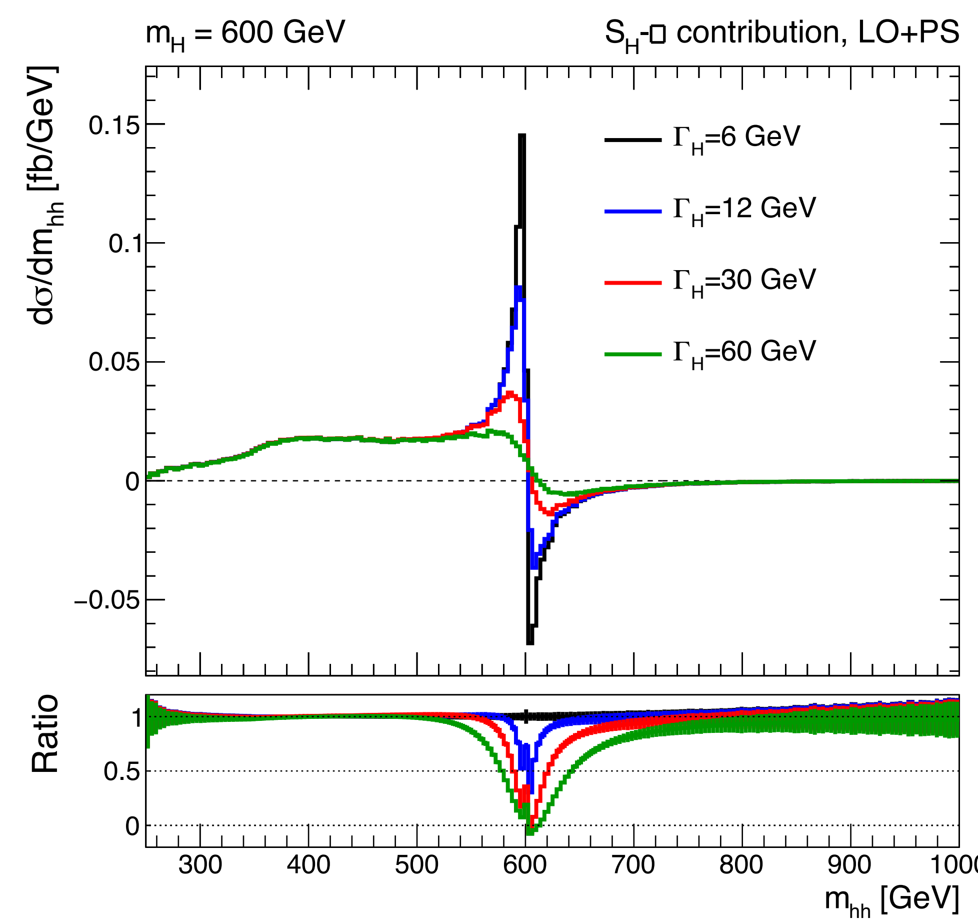


HH→4b-like smearing

Narrow width approximation (NWA) validity

- In singlet model, largest relative width we found was 1.2% - BM9
- Usually this is within experimental resolution so NWA for generation of S_H is valid
  - Generate sample with narrow width (e.g 20 MeV as below) and then rescale the branching ratio by $(20\,\mathrm{MeV})/\Gamma_H$ (left plot)
  - Caution: this is specific to singlet model, other models can accommodate larger widths O(10%)
- But such a re-scaling is not possible for interference terms!
  - Shapes of distributions depends on width in non-trivial way (e.g right plot)





Benchmark distributions (BM1)

- Some other example of variables after smearing
- We show different assumptions for the modelling
  - Blue = full, correct description, Green = resonant-only (most CMS and ATLAS results so far), magenta = SM non-resonant + resonant with no interference (few analyses do this already)