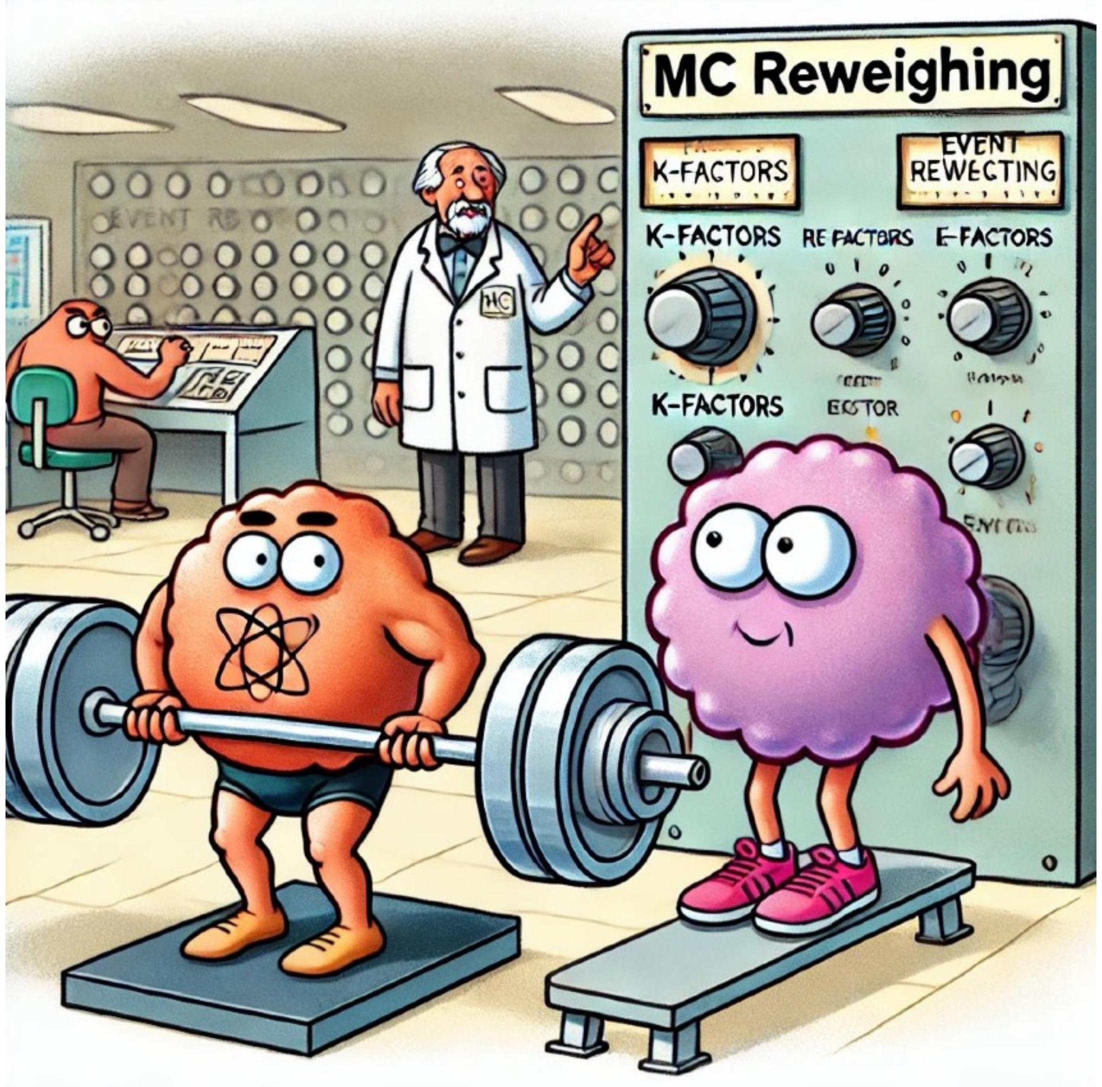
IMPERIAL

Di-Higgs reweighing tutorial



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LHC WG4 meeting March 12
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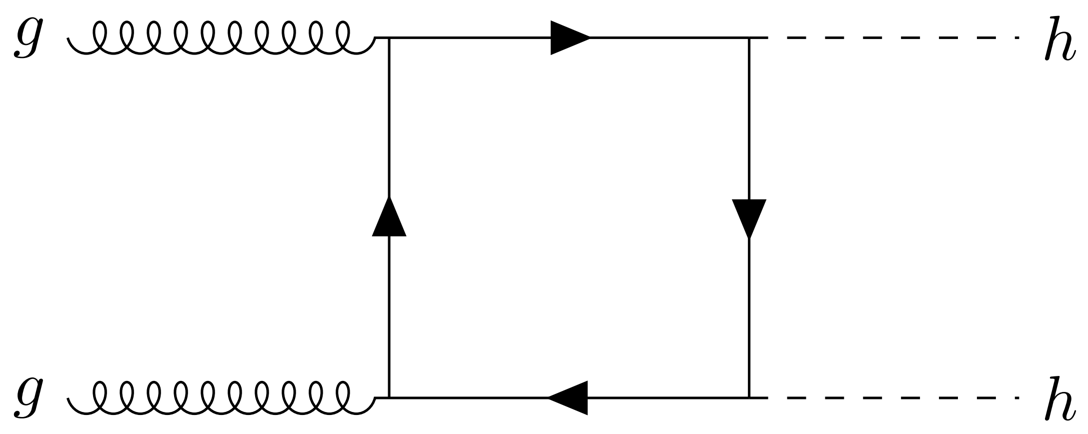
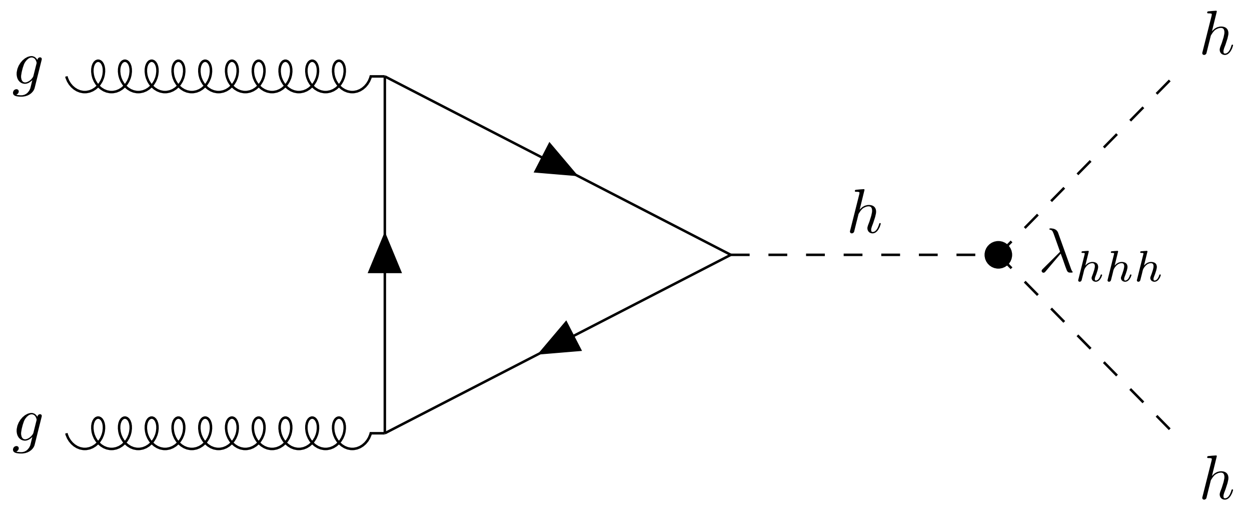
Overview

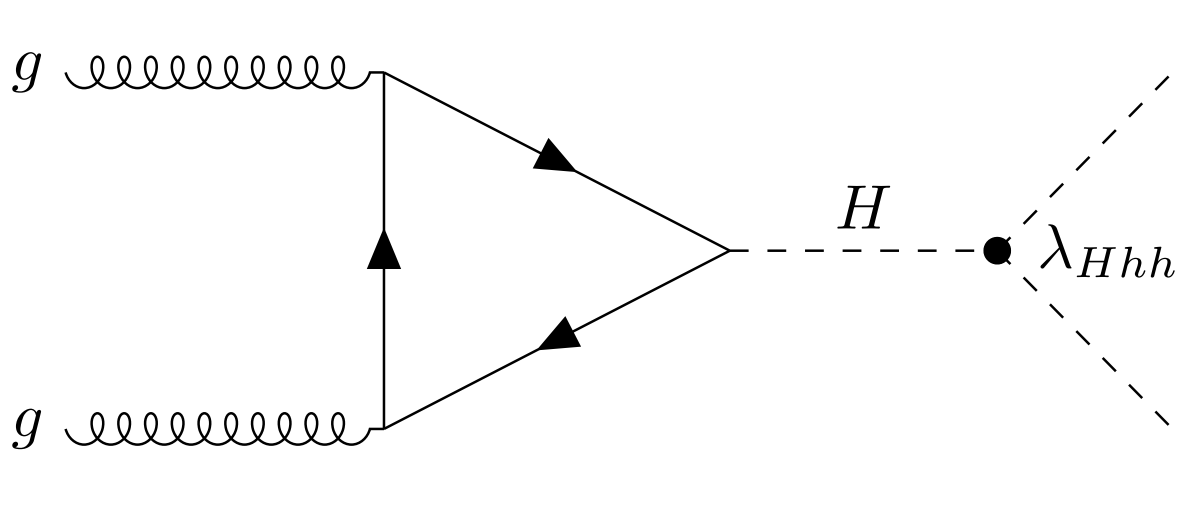
- The material shown today based on the paper "**Interference effects in resonant di-Higgs production at the LHC in the Higgs singlet extension**", in collaboration with F. Feuerstake, E. Fuchs, and T. Robens
  - arXiv:2409.06651
- Today I will focus on the method we used for reweighing di-Higgs events to account for inteference effects between resonant and non-resonant di-Higgs processes
- If there is time I will also show how to generate di-Higgs nonresonant and resonant MC events using Madgraph
- These slides will give a quick introduction then we will move to Google Colab notebooks

di-Higgs production at the LHC

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





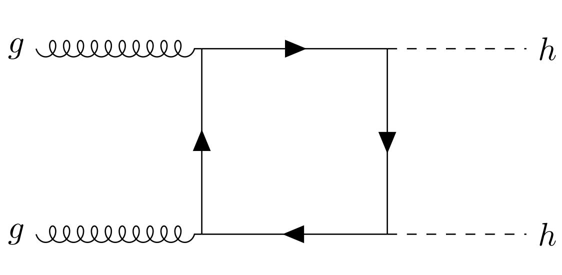


ME reweighing method

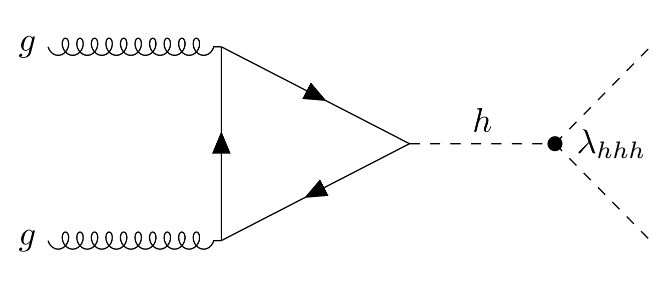
- ME reweighing reweighs events using:

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

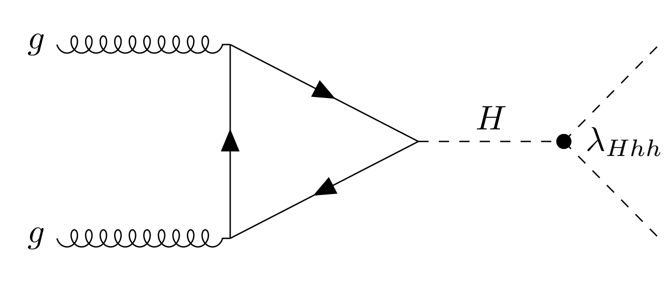
- $\mathscr{M}_{\text{ref}}$ is ME for the MC you are reweighing and $\mathscr{M}_{\text{target}}$ is the ME for the process/parameters you want to model
  - $\mathscr{M}_{\text{target}}$ in general model dependent, many options for process and parameters
  - In our method we decompose $\mathscr{M}_{\text{target}}$ 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)



$= \Box$



$= S_h$

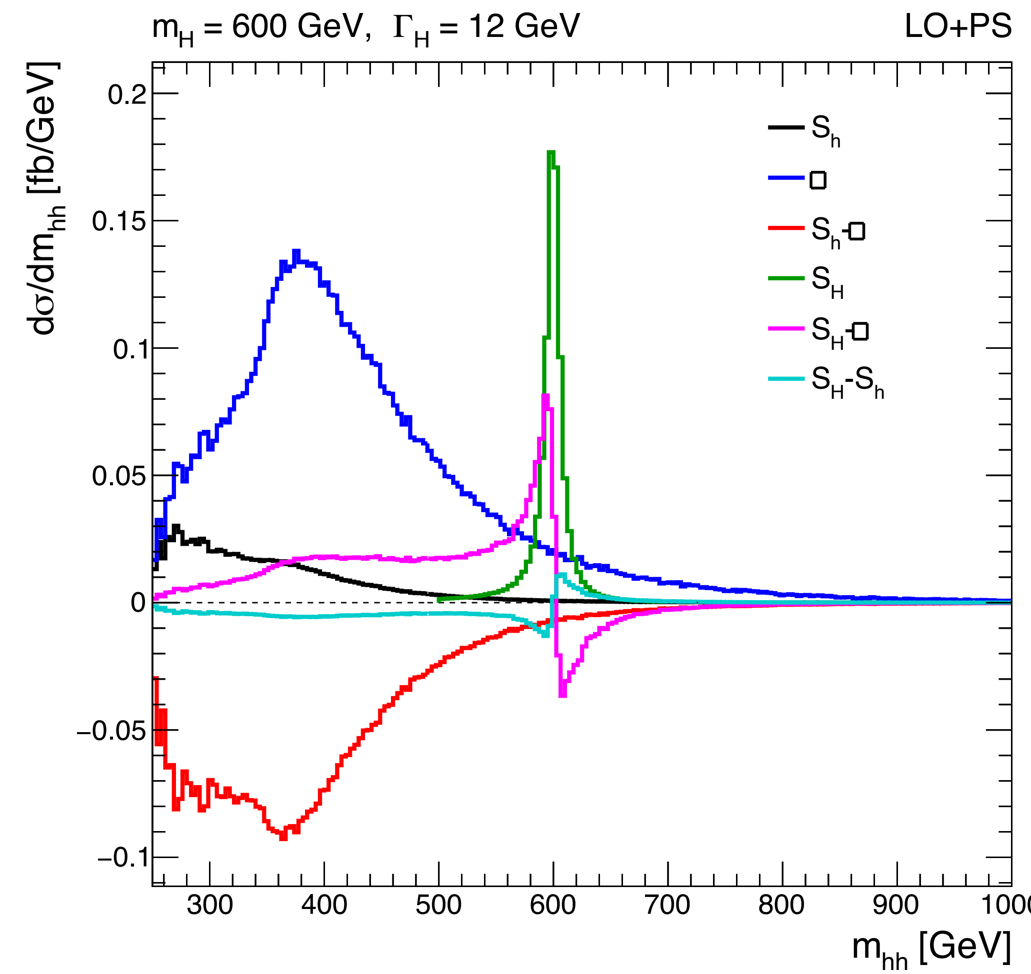


$= S_H$

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

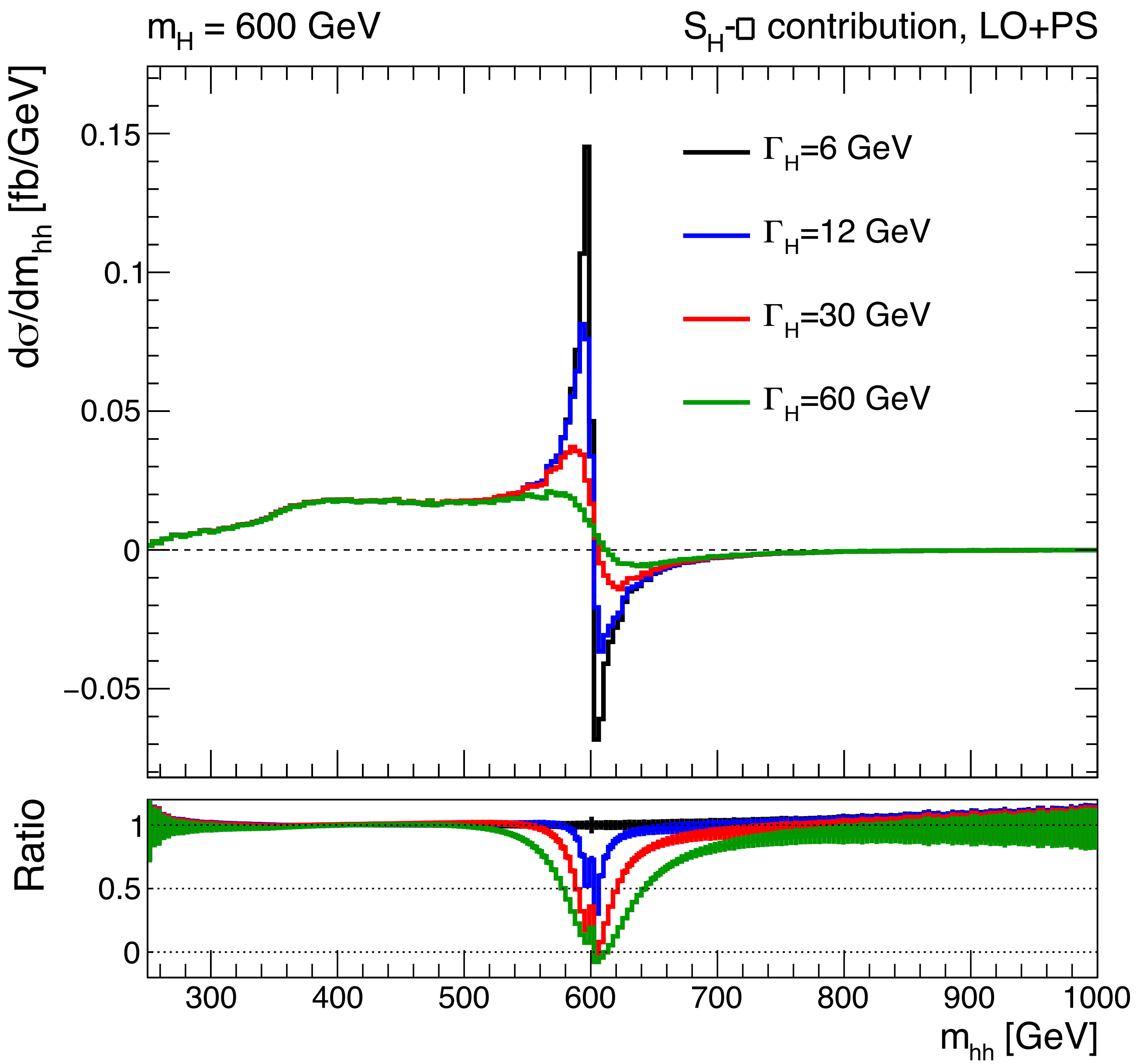
$$
\begin{aligned}
|\mathcal{M}_{\mathrm{total}}|^2 = {} & \mathcal{M}_{\Box}^{\,2} \cdot (\kappa_q^h)^4 \\
& + \mathcal{M}_{S_h}^{\,2} \cdot (\kappa_q^h)^2 \kappa_{\lambda_{hhh}}^2 \\
& + \mathcal{M}_{S_H}^{\,2}(m_H, \Gamma_H) \cdot (\kappa_q^H)^2 \kappa_{\lambda_{Hhh}}^2 \\
& + \widetilde{\mathcal{M}}_{S_h-\Box}^{\,2}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

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

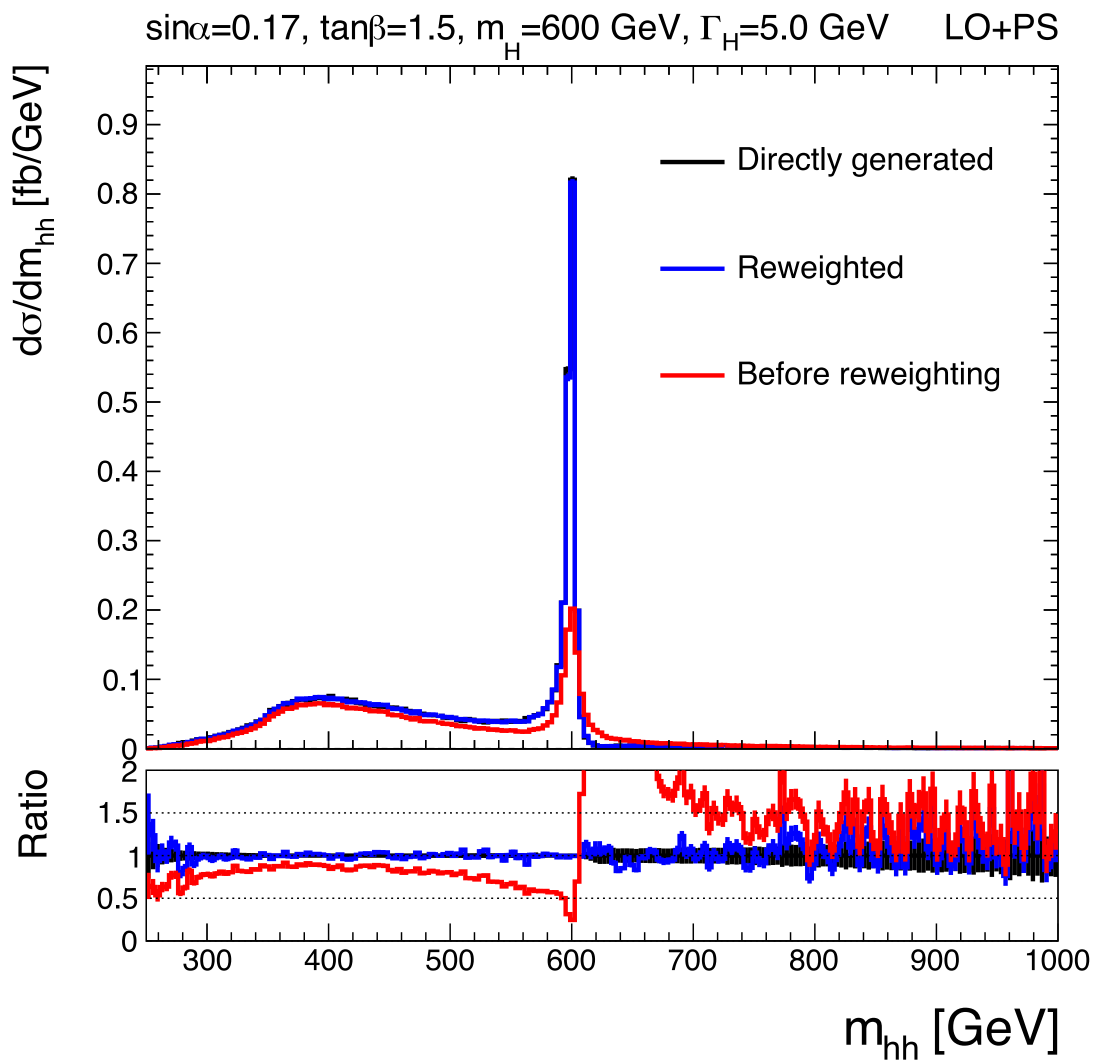
- With ME reweighing you need to make sure your chosen reference sample is populated in all phase-space regions where $\mathscr{M}_{\text{target}}$ is non-vanishing

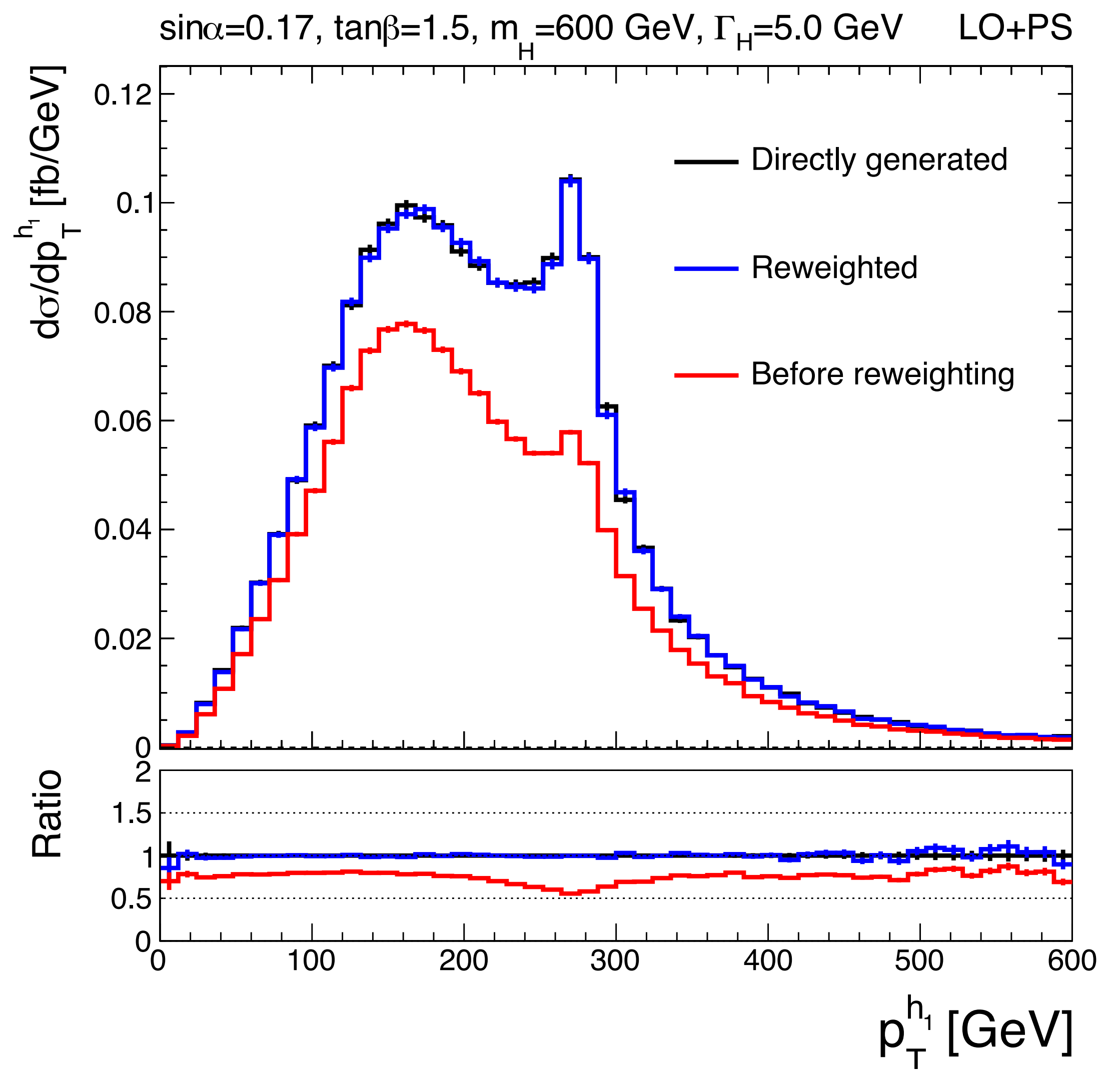
- For the $\square$, S_h, $\square - S_h$, $\square - S_H$, and $S_H - S_h$ contributions we use a SM di-Higgs sample (non-resonant only)

- 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)

Validating the reweighing method

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





- Now lets move to some examples in Google Colab

- Example using reweighing tool: https://colab.research.google.com/drive/1kqu-9ouFCXNKJFB8dC0OHUdpsk1BxtiR?usp=sharing

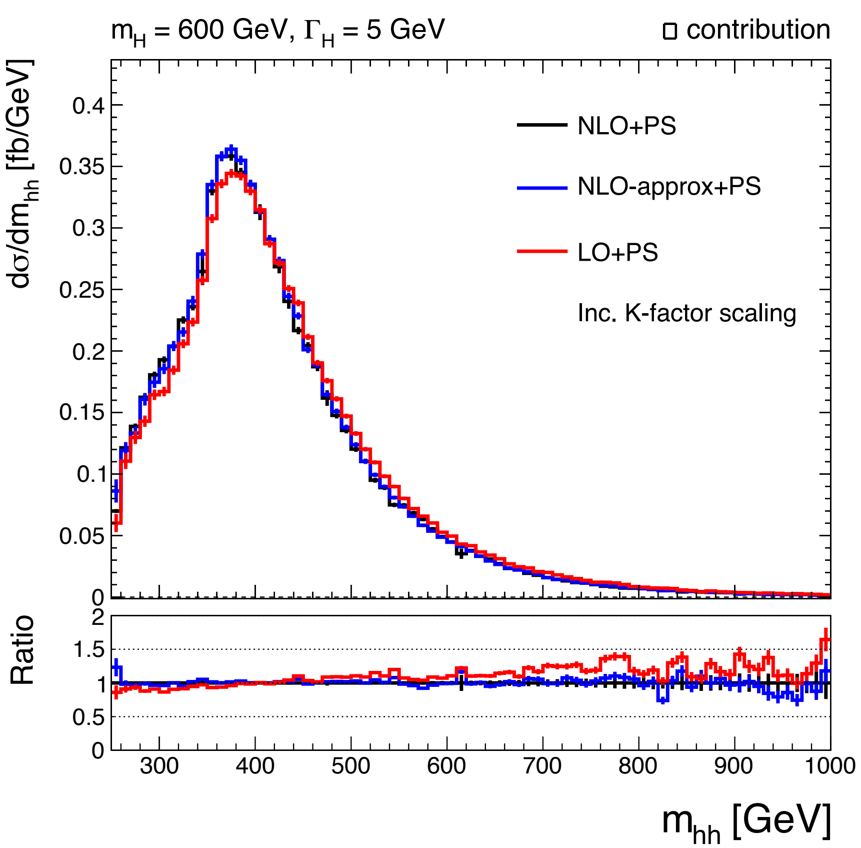
- Example generating MC using Madgraph: https://colab.research.google.com/drive/1SGzp8BiuV9XGM_9QKUOLrsar3-LYvN4-?usp=sharing

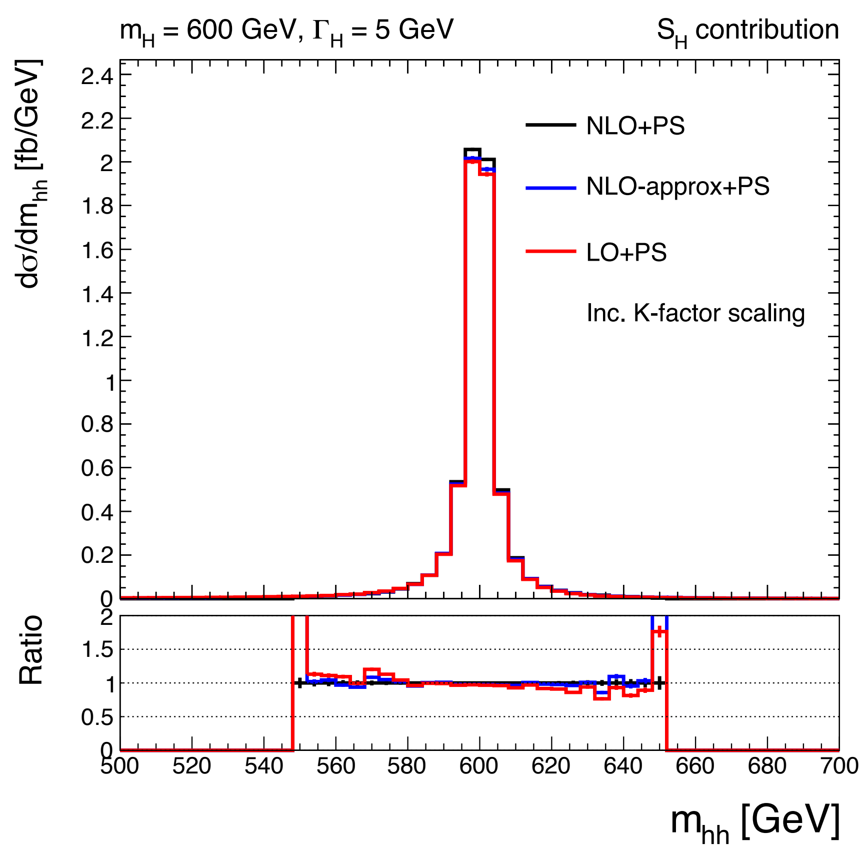
- Reweighing tool available on Gitlab: https://gitlab.com/danielwinterbottom/HHReweighter

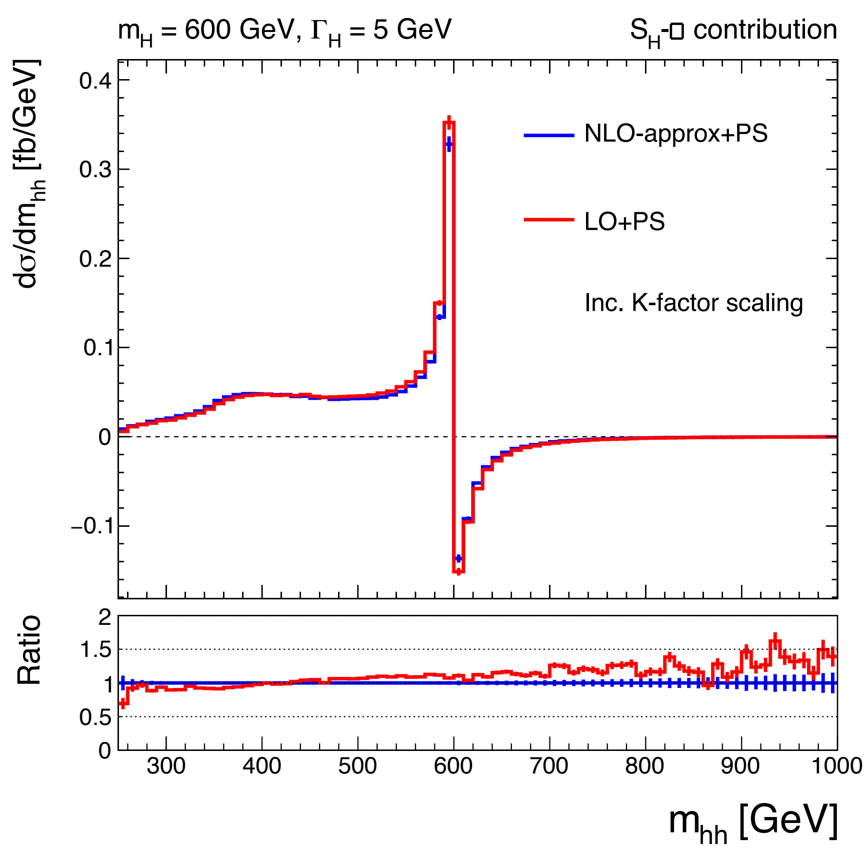
Backup

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 $\square$, S_h, $\square - S_h$ for non-resonant, and S_H resonant samples and compare to reweighing where possible
  - We can also use reweighing to obtain approximate $\square - S_H$, and $S_H - S_h$ predictions - agree well with LO, to be checked once proper NLO MC is available

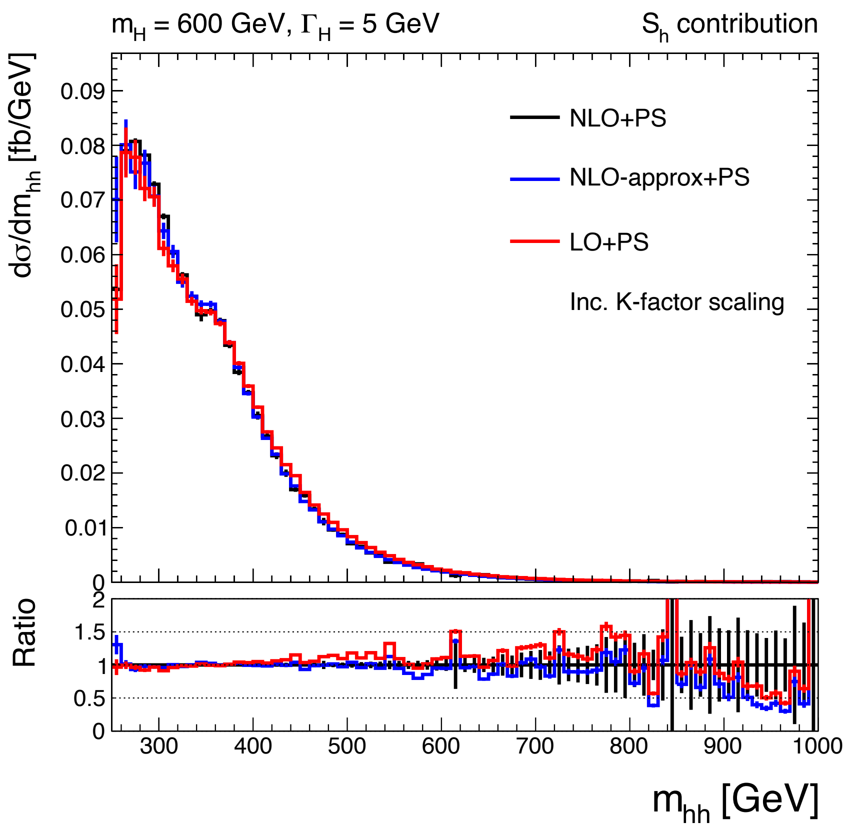


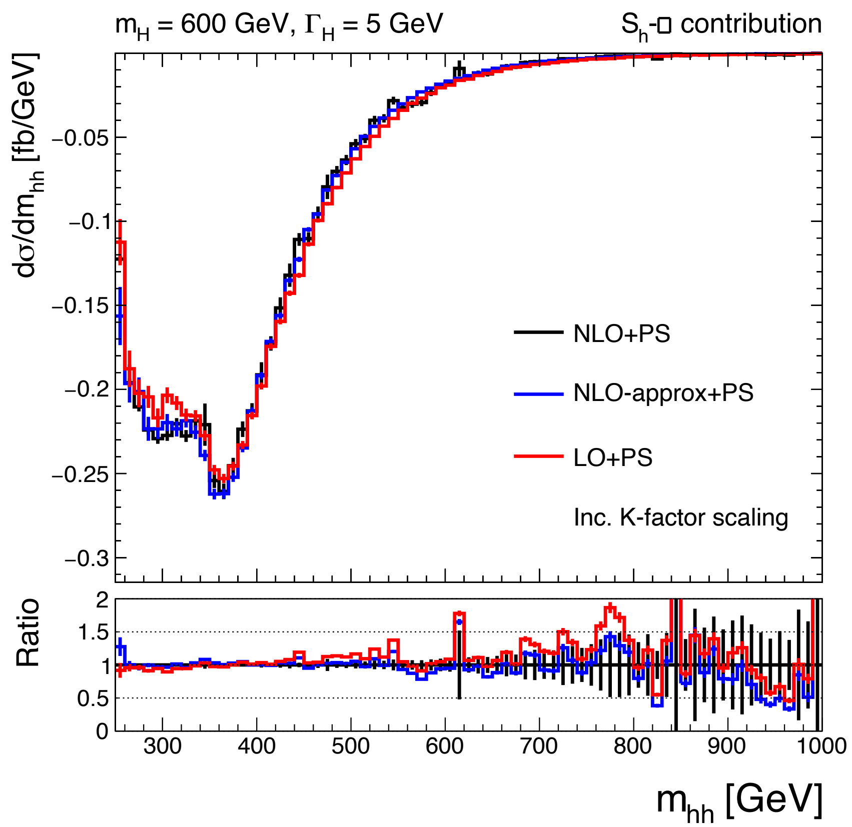


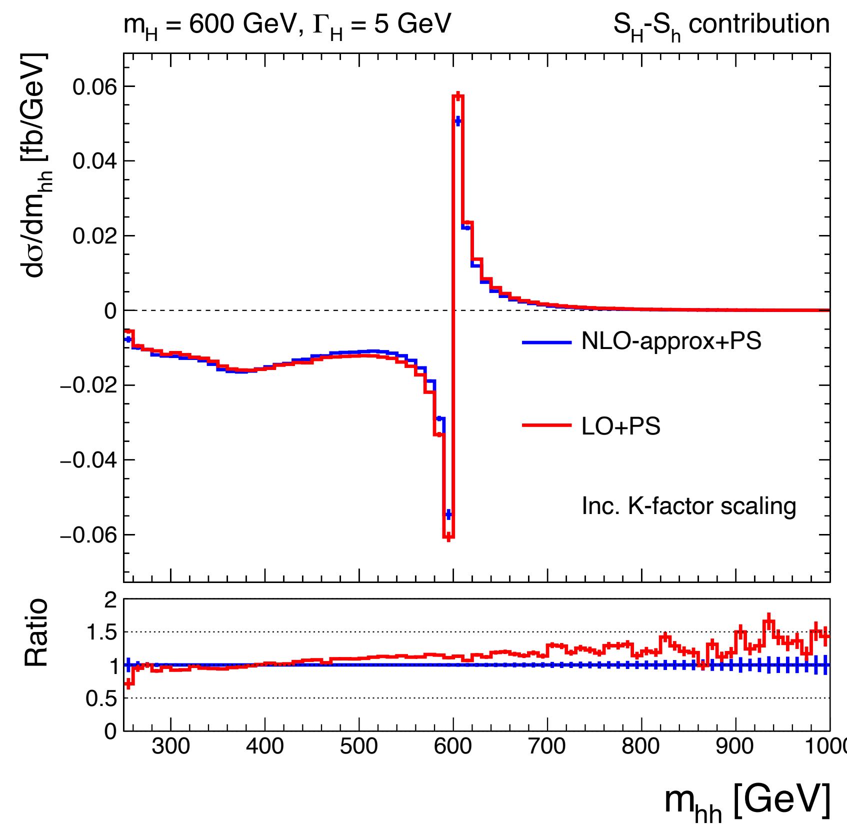


Additional plots of NLO validations

- Plots of di-Higgs mass for other terms

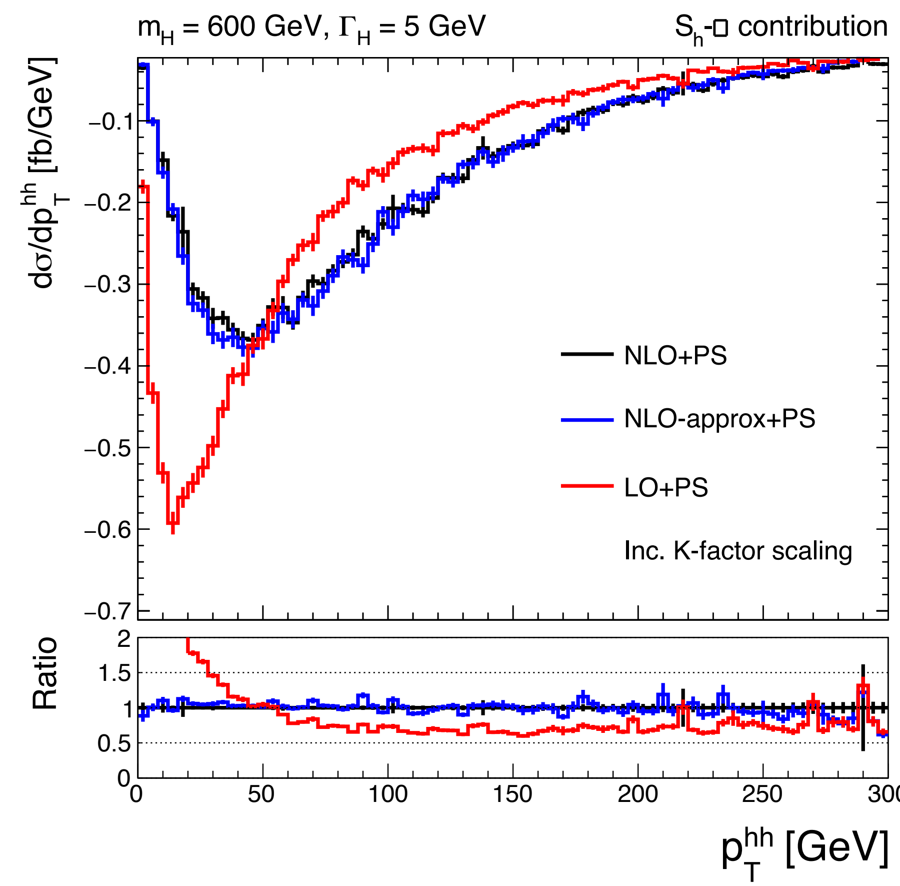


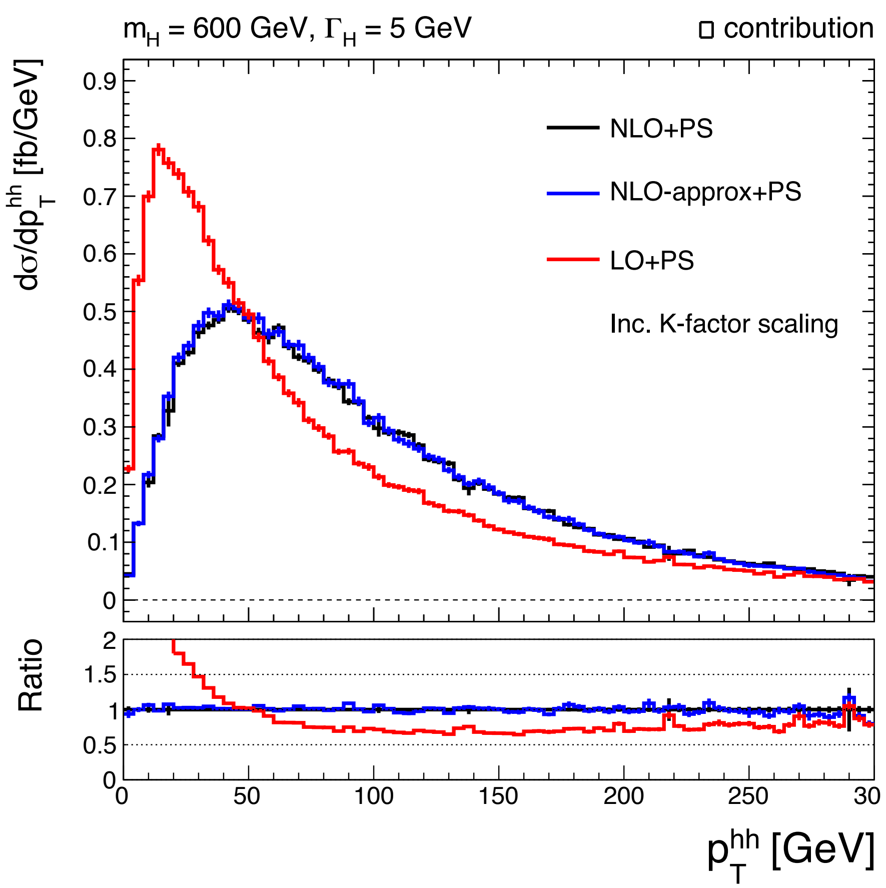


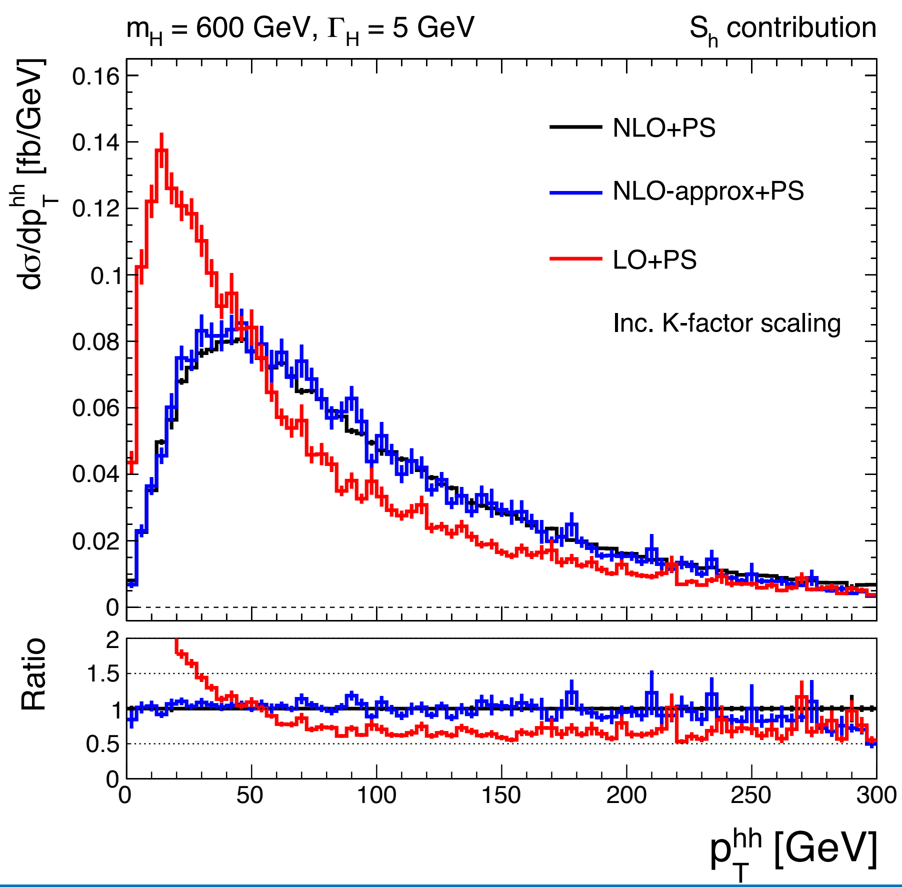


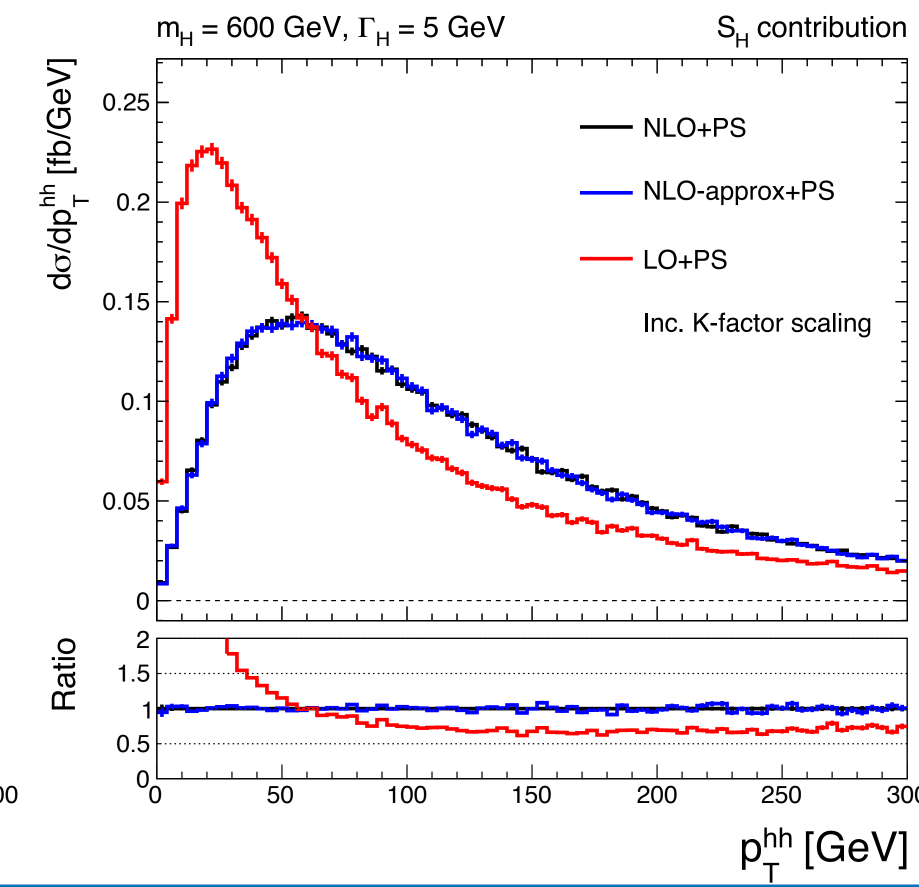
Additional plots of NLO validations

- Plots of di-Higgs p_T









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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

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

Couplings / Width

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

$$\kappa^h_{f/V} = \cos\alpha,$$

$$\kappa^H_{f/V} = \sin\alpha,$$

$$\kappa_{\lambda_{hhh}} = \cos^3\alpha - \tan\beta\sin^3\alpha,$$

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

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