An Optimal Strategy for the Experimental H/A $\rightarrow t\bar{t}$ Search

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Spanish LHC Network Meeting
4-6 November 2020

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Introduction

- CIEMAT Technical Report 1472 (also available as CMS Analysis Note)

CIEMAT Technical Report 1473

Optimal Generator Level Strategy for the Experimental $gg \to H/A \to t\bar{t}$ Search

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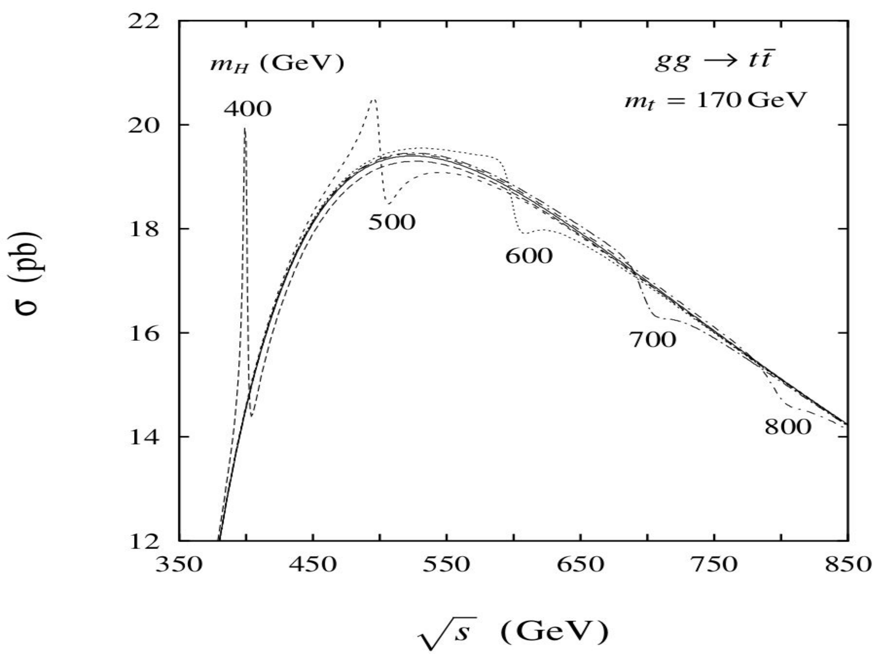
Abstract

We revisit the generator predictions for the $gg \to t\bar{t}$ process in the presence of new scalars and/or pseudoscalars at order $\mathcal{O}(\alpha_s^2)$ (LO) in QCD, taking into account all amplitude interferences and spin correlations down to the final top decay products. The resulting expressions are rather simple, and can be used to set up a convenient reweighting method for the experimental analysis of LHC data. The proposed procedure only requires the generation of a large $pp \to t\bar{t}$ standard model sample, and it is expected to be statistically precise as long as the $gg \to H/A \to t\bar{t}$ distortions on top of the standard model background are not too large. Extensive comparisons with the results of an automatized LO generator are presented. We also discuss the effect of considering an energy-dependent Higgs width and some of the limitations of current approaches due to missing higher order QCD effects.

Short reminder of pp→H→ttbar search

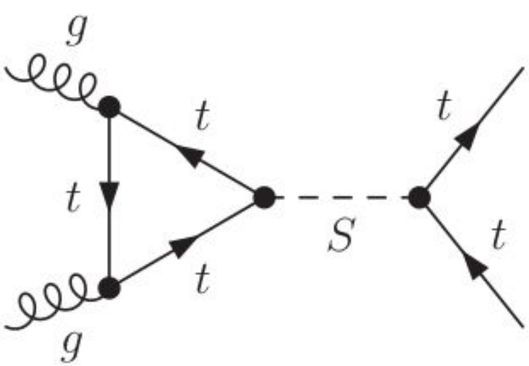
- New H/A resonance, predominantly coupling to ttbar
- Dominant gluon fusion mechanism
- Non-negligible interference effects with SM gg->ttbar, particularly at large masses/widths

gg→tt̄ cross section

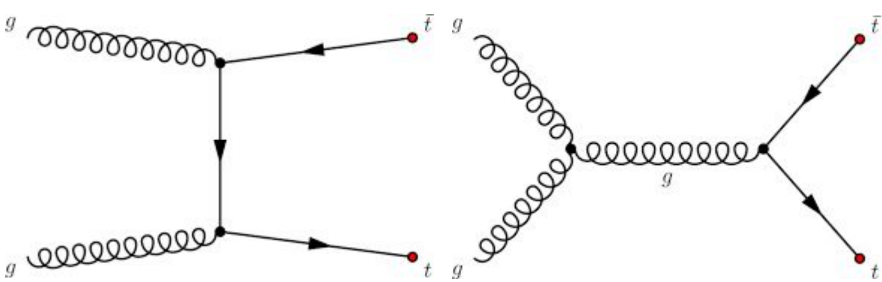


(D. Dicus A. Stange, S. Willenbrock, arXiv:hep-ph/9404359)

gg→tt̄ signal

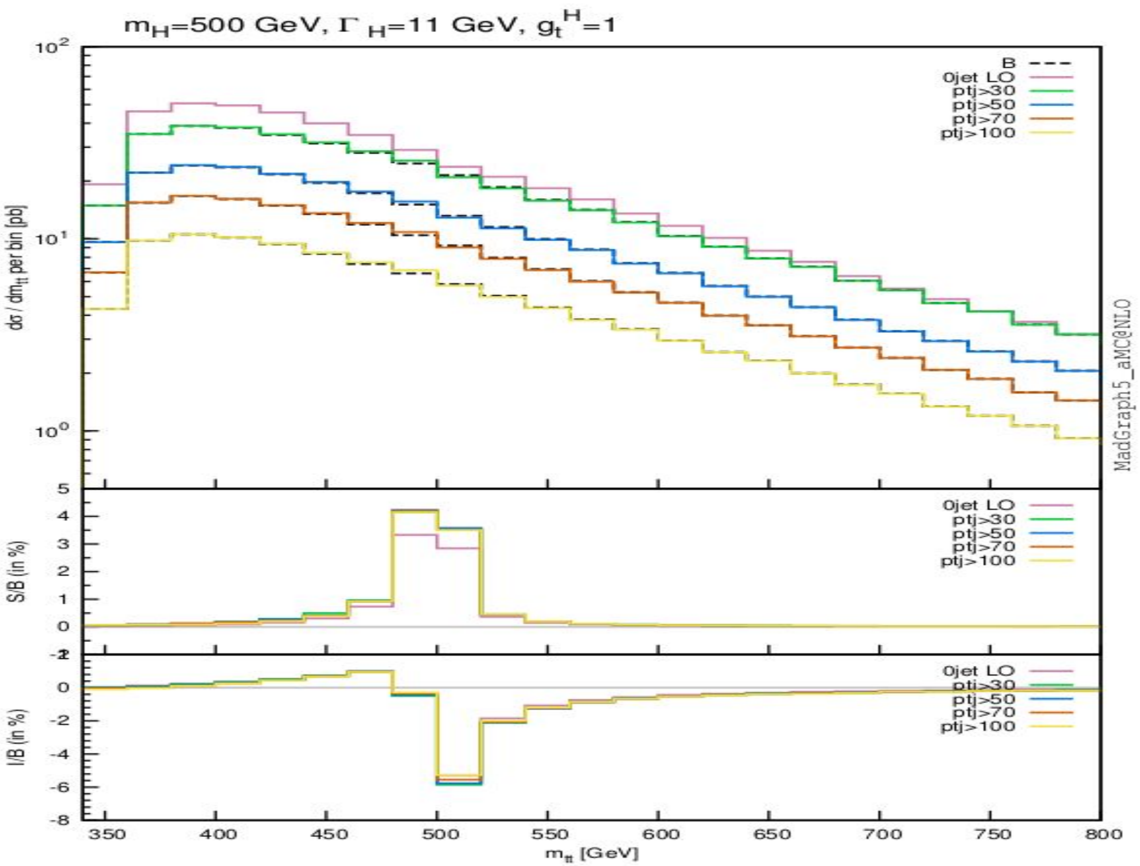


gg→tt̄ background



Short reminder of pp→H→ttbar search

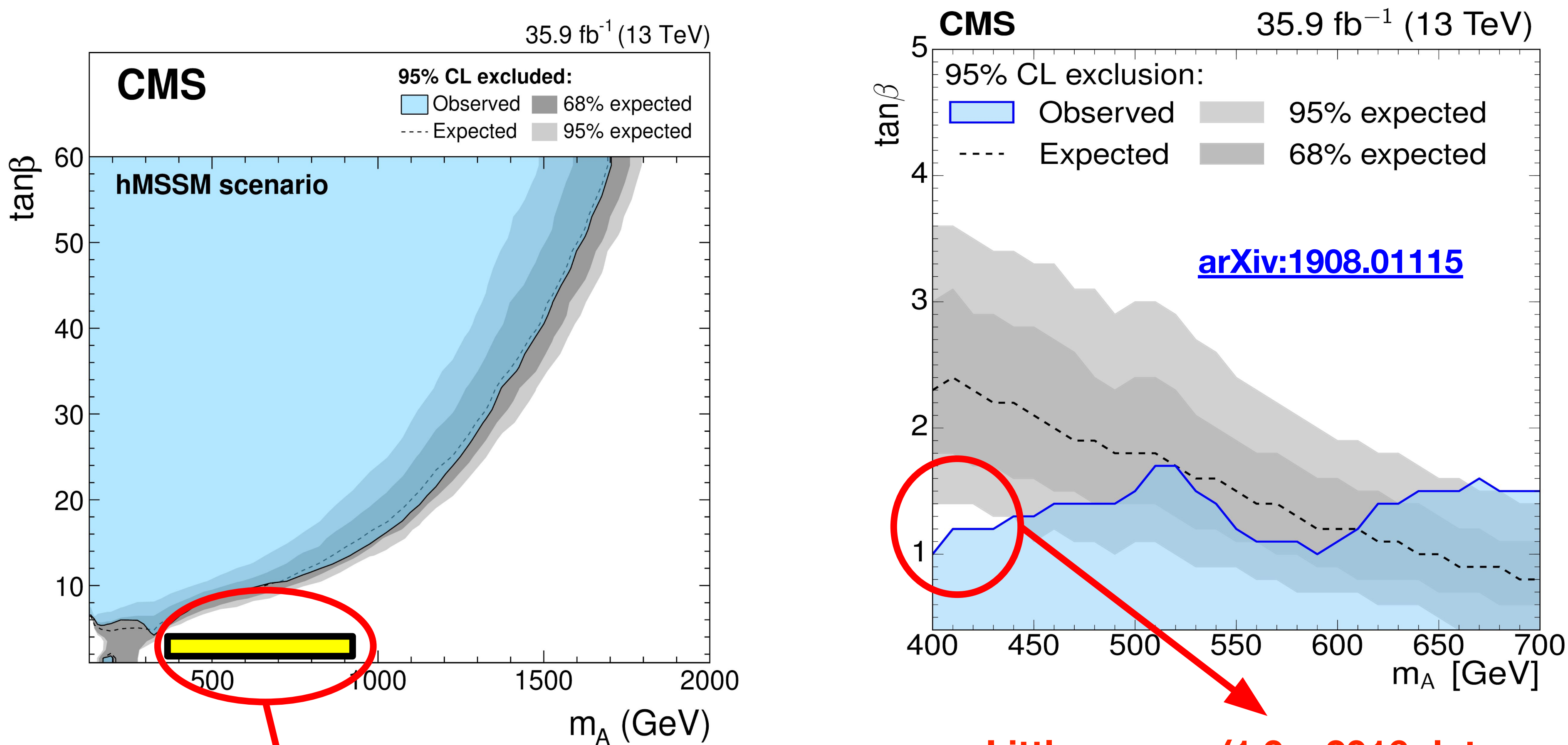
- "Wiggle" effects distorted by PDF convolution in pp→$t\bar{t}$. Invariant mass of $t\bar{t}$ system:



- And this plot assumes ideal detector identification/resolution
- The measured mass comes from a kinematic fit ⇒ more dilution
- The experimental analysis is complicated

B. Hespel, F. Maltoni, E. Vryonidou, arXiv:1606.04149

Complementary to $H \to \tau\bar{\tau}$ searches



$H \to t\bar{t}$

Little excess (1.9σ, 2016 data, driven by 2l+jets analysis)

H→ttbar dissected

- **Parton-level differential cross section down to the top-quark level (general case with H and A bosons, z=cosϑ in CM):**

$$\frac{d\sigma(gg\to t\bar{t})}{dz} = \frac{\alpha_s^2 G_F^2 m_t{}^2 s^2}{1536\pi^3}\beta^3 \left|\frac{N(\sqrt{1-4m_t{}^2/s},\lambda_t)}{s-m_H^2+im_H\Gamma_H(s)}\right|^2$$ **H resonant**

H interference
$$- \frac{\alpha_s^2 G_F m_t{}^2}{48\pi\sqrt{2}}\left(\frac{\beta^3}{1-\beta^2 z^2}\right)\mathrm{Re}\left[\frac{N(\sqrt{1-4m_t{}^2/s},\lambda_t)}{s-m_H^2+im_H\Gamma_H(s)}\right]$$

A resonant
$$+ \frac{\alpha_s^2 G_F^2 m_t{}^2 s^2}{1536\pi^3}\beta \left|\frac{P(\sqrt{1-4m_t{}^2/s},\lambda_t')}{s-m_A^2+im_A\Gamma_A(s)}\right|^2$$

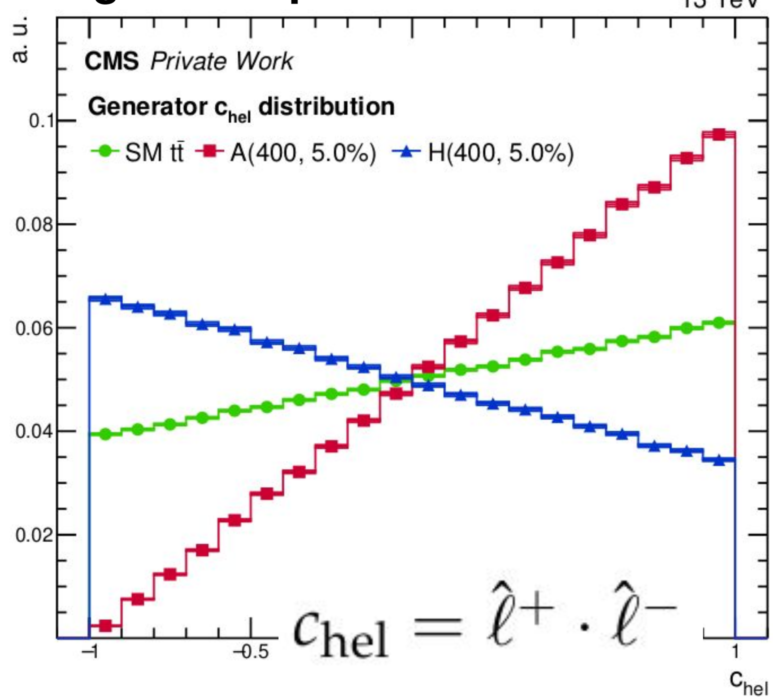
A interference
$$- \frac{\alpha_s^2 G_F m_t{}^2}{48\pi\sqrt{2}}\left(\frac{\beta}{1-\beta^2 z^2}\right)\mathrm{Re}\left[\frac{P(\sqrt{1-4m_t{}^2/s},\lambda_t')}{s-m_A^2+im_A\Gamma_A(s)}\right]$$

SM ttbar
$$+ \frac{d\sigma_{QCD,\,gg\to t\bar{t}}}{dz}$$

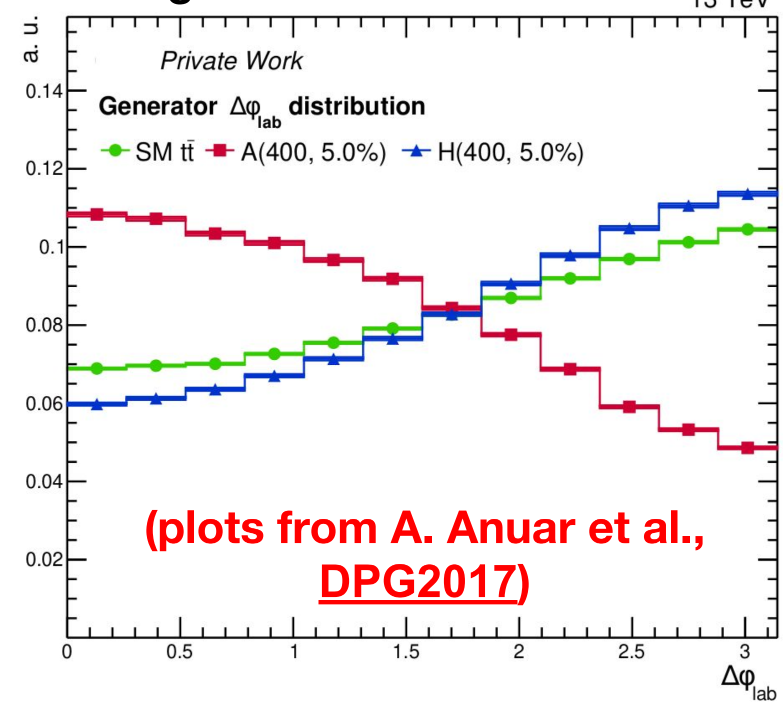
Short reminder of H→ ttbar features

- **The presence of these scalars also modify the interference effects between top and antitop products, which are better visible via angular correlations between W decay products**
- **Most sensitive experimental variable: azimuthal angle difference between leptons (or down-type quarks of W decay in general)**

Angles in top rest frames



Angles in LAB frame



The calculation

- **We have calculated explicitly/analytically the full matrix element and differential cross for section gg->ttbar at LO, down to the final state particles (i.e. including top decays), in the presence of H/A bosons:**

- **The relevant term (for same helicity colliding gluons in a color-singlet state) is:**

$$\frac{1}{16\pi^2}\frac{d\sigma^{same-gluon-hel,interf}_{gg\to t\bar{t}}}{dz\,d\Omega_1\,d\Omega_2} = \frac{4m_t{}^2}{s}\frac{\pi\alpha_s^2\beta}{48s(1-\beta^2z^2)^2}\cdot \left|1-\frac{\sqrt{2}s^2\,G_F(1-\beta^2z^2)}{16\pi^2}\,\frac{P(\sqrt{1-4m_t{}^2/s},\lambda_t')}{s-m_A^2+im_A\Gamma_A(s)}\right|^2\cdot [1+\cos\theta_1\cos\theta_2+\sin\theta_1\sin\theta_2\cos(\phi_1-\phi_2)]$$
$$+\ \frac{4m_t{}^2}{s}\frac{\pi\alpha_s^2\beta^3}{48s(1-\beta^2z^2)^2}\cdot \left|1-\frac{\sqrt{2}s^2\,G_F(1-\beta^2z^2)}{16\pi^2}\,\frac{N(\sqrt{1-4m_t{}^2/s},\lambda_t)}{s-m_H^2+im_H\Gamma_H(s)}\right|^2\cdot [1+\cos\theta_1\cos\theta_2-\sin\theta_1\sin\theta_2\cos(\phi_1-\phi_2)]$$

(ϑ_1, ϑ_2, ϕ_1, ϕ_2 are the spherical angles of the down-type fermions from the W decays, after a boost to their respective top rest frames)

LO validation against MadGraph (MG) LO

- **Comparison of total cross sections between MG implementation and the reweighted MC ttbar standard samples OK at the % level**
  - **Coupling, scales, ..., previously matched to agree within that precision**

Type of deviation	$m_{\mathrm{H}} = 400$ GeV	$m_{\mathrm{H}} = 600$ GeV	$m_{\mathrm{H}} = 800$ GeV	$m_{\mathrm{H}} = 1.0$ TeV
Resonant	1.3%	0.5%	1.0%	0.3%
Interference	0.9%	−0.1%	−0.9%	1.1%

Type of deviation	$m_A = 400$ GeV	$m_A = 600$ GeV	$m_A = 800$ GeV	$m_A = 1.0$ TeV
Resonant	1.1%	−0.1%	0.2%	−1.5%
Interference	0.8%	−1.6%	−0.3%	0.2%

Table 1: Relative difference between reference (LO) and LO-reweighted cross sections. Resonant and interference term differences are shown separately, for different values of scalar and pseudoscalar Higgs masses. Both measurements use the same factorization/renormalization scale ($\mu^2 = m^2(\mathrm{t\bar{t}}) + p_T^2(\mathrm{t\bar{t}})$). Statistical uncertainties are better than 1%, while systematic uncertainties are expected to be at least one order of magnitude larger.

LO validation against MadGraph (MG) LO

- **χ^2 tests of shapes for the most relevant variables in the analysis:**
  - **The invariant mass of the ttbar system, m_{tt}**
    - It tests the complicated structure of the interference with the SM
  - **The azimuthal difference between the two down-type fermions from the W decays (in their top rest frames), $\Delta\phi_{ll}$**
    - It tests the implementation of spin correlations

(PLOTS OF COMPARISON IN BACKUP)

Type of deviation	$m_H = 400$ GeV	$m_H = 600$ GeV	$m_H = 800$ GeV	$m_H = 1.0$ TeV
$m_{t\bar{t}}$, resonant	59.19/49	53.47/49	38.86/49	35.28/49
$\Delta\phi_{ll}$, resonant	13.77/9	2.47/9	5.60/9	9.14/9
$m_{t\bar{t}}$, interference	36.16/49	37.99/49	47.69/49	43.93/49
$\Delta\phi_{ll}$, interference	1.76/9	4.06/9	7.51/9	14.74/9

Type of deviation	$m_A = 400$ GeV	$m_A = 600$ GeV	$m_A = 800$ GeV	$m_A = 1.0$ TeV
$m_{t\bar{t}}$, resonant	58.33/49	30.95/49	37.15/49	57.65/49
$\Delta\phi_{ll}$, resonant	10.92/9	2.79/9	10.29/9	9.74/9
$m_{t\bar{t}}$, interference	47.34/49	34.90/49	24.96/49	69.93/49
$\Delta\phi_{ll}$, interference	7.82/9	2.43/9	10.77/9	4.85/9

Table 2: χ^2 per degree of freedom of the comparison between reference (LO) and LO-reweighted signal distributions. The two most relevant observables ($t\bar{t}$ mass and top rest frame lepton azimuthal difference) are shown for the resonant and interference cases, scalar and pseudoscalar cases.

And now, let us reweight...

- **Having the complete (simple) expressions of the differential cross section with and without BSM effects gives us the capability to use a matrix-element based reweighting method in the analysis. This is justified as long as the observed deviations from SM are small. For each event, the weight is given by:**

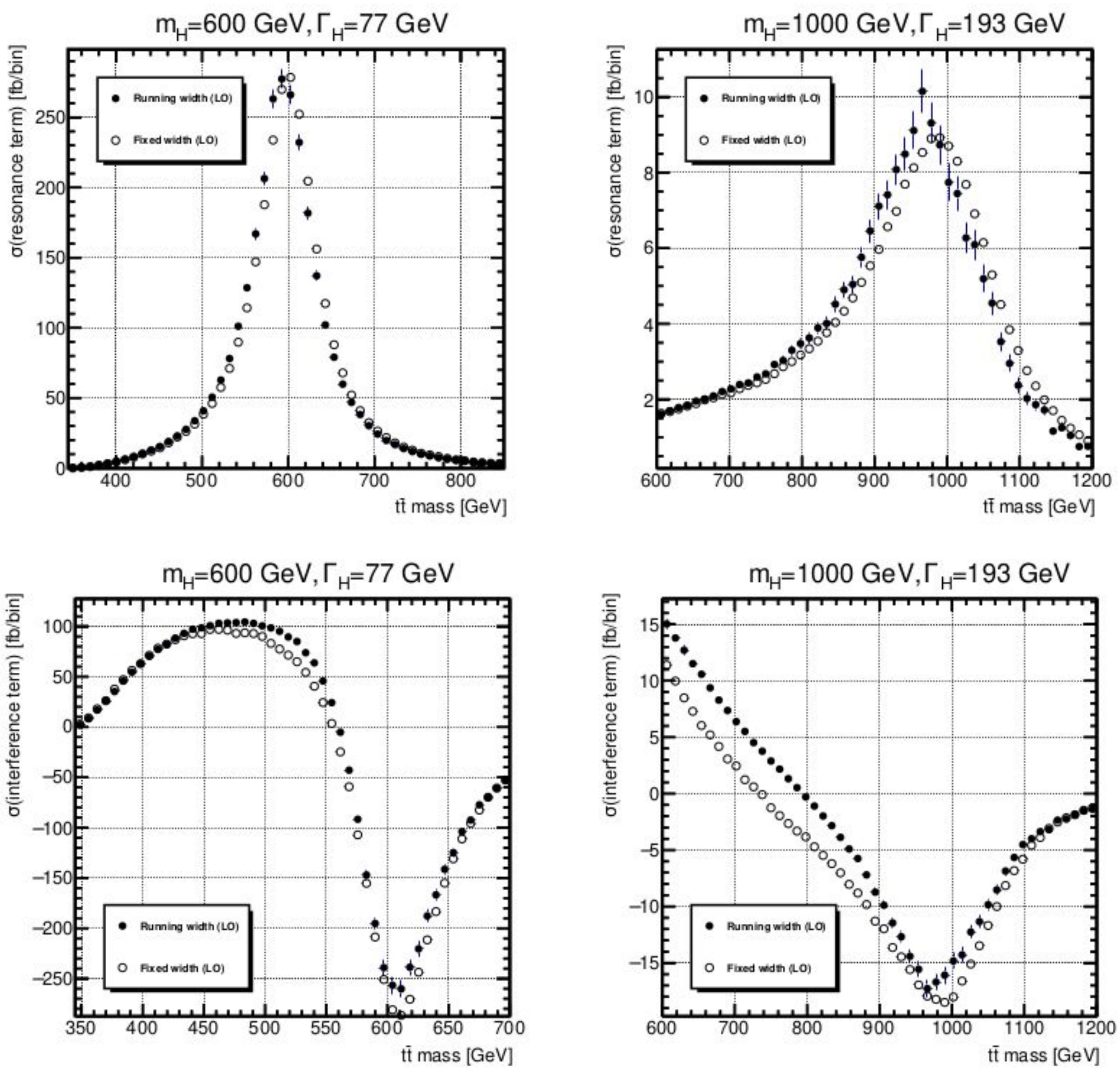
$$\mathcal{W}(\beta, z, \Omega_1, \Omega_2; m_H, m_A, \lambda_t, \lambda_t') = \frac{\left(\frac{d\sigma_{gg\to t\bar{t}}(m_H, m_A, \lambda_t, \lambda_t')}{dz\, d\Omega_1\, d\Omega_2} \right)}{\left(\frac{d\sigma_{QCD, gg\to t\bar{t}}}{dz\, d\Omega_1\, d\Omega_2} \right)}$$

(β is the top velocity in the gg center-of-mass frame, and λ_t is the H coupling to the top quark. The A coupling to the top quark could be different in general, and it is denoted by λ'_t)

Advantages of a reweighting approach

- It allows an analysis with huge MC statistics, both for signal and background, because only a “huge” ttbar reference sample is needed (Run3, …)
- It ensures a consistent treatment of the input parameters and couplings for the SM and BSM processes, as opposed to independent Monte Carlo productions that typically have different inputs for signal and background (scales, …).
- The estimate of systematic uncertainties gets also simplified because in many cases the variations can also be implemented via weights on the same individual events (no spurious statistical uncertainties)
- No need to generate too many BSM signal samples with many different masses or widths, thus making it almost trivial the interpolation of expectations and the extraction of final results as a function of the mass and the width of the new resonances.
- In the limit of perfect detector resolution/kinematic reconstruction (unfortunately not the case for H→ttbar) the event weight using reconstructed quantities is an **optimal variable** for the analysis (=> no need to perform a multivariate analysis).

Implementing a √s-running scalar width



- Here we compare the results with and without a running width using the reweighting procedure
- The effect is visible for masses ≳600 GeV
- Spin-correlation distributions (not shown here) are almost unaffected

Going to NLO and more advantages ...

- **No full NLO calculation is available as of today (to the best of our knowledge**
    - **Current analyses perform ad-hoc k-factor corrections that are just "guesses/hopes"**

- **The method described in this Note can also be applied on a sample of SM tt events generated at NLO precision, using a variety of programs publicly available (aMC@NLO, POWHEG,...). This approach - denoted as "LO-like reweighting" in MADGRAPH - is not expected to be NLO accurate, but should be able to absorb most of the higher order corrections that have a soft-collinear character.**
    - **The main shape effect of this LO-like NLO reweighting is a change in the polar angle distribution of the top with respect to LO (see backup slides)**

- **One fact that I have not highlighted until now is that this reweighting method can be easily extended to other BSM scenarios. The loop functions can be easily changed to match our preferred BSM scenario, for instance adding new particles running in the loop. Many of alternative scenarios for the loop are already given in the literature.**

- **The expressions can also be used for scalar masses below the threshold (m_A=300 GeV, for instance), provided one does not analyze ttbar masses below the ttbar threshold (due to the large weights and the lack of enough reference ttbar events in that region)**

Summary/outlook

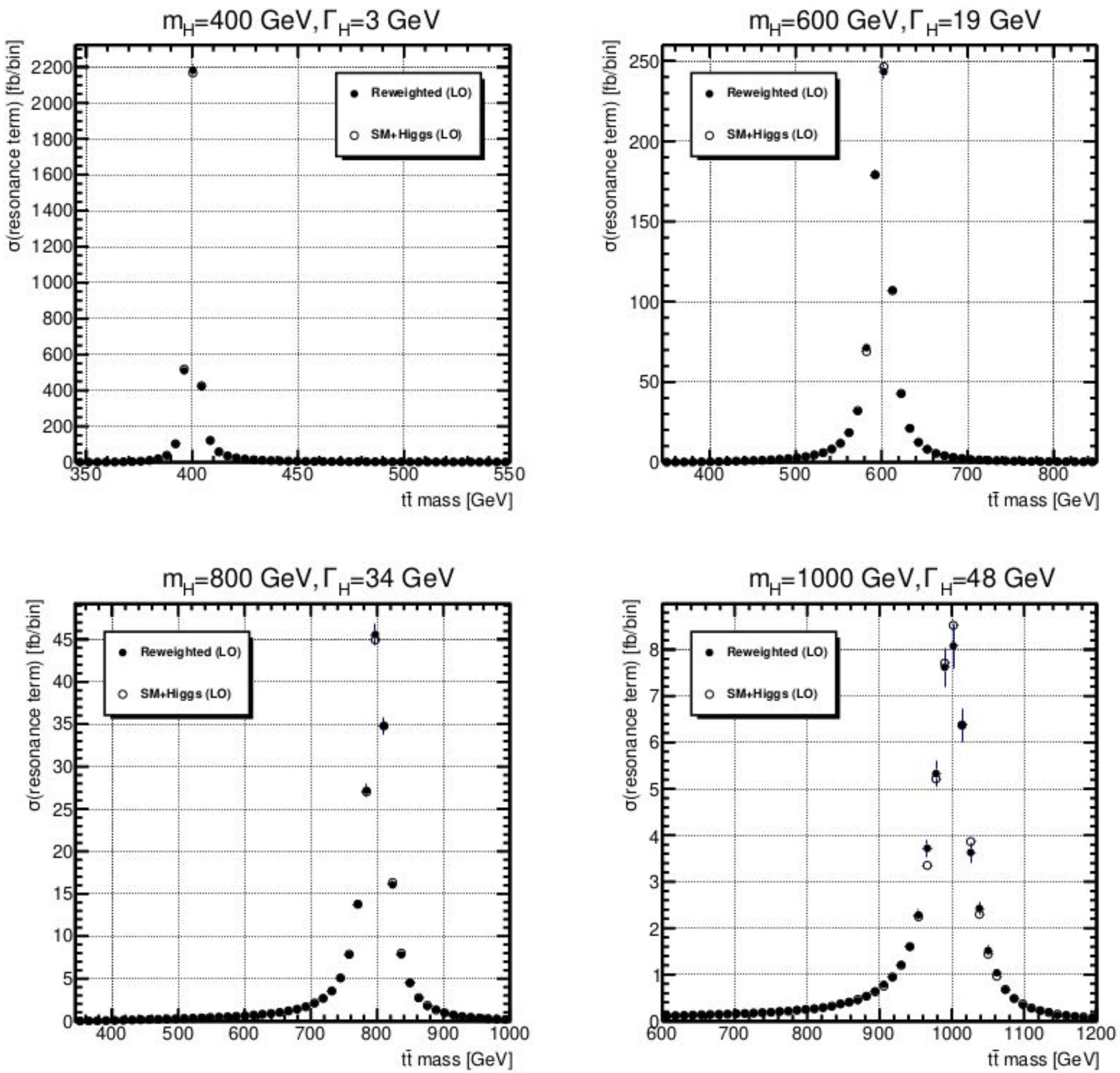
- Simple pp → H/A → ttbar reweighting procedure at LO implemented:
  - Almost perfect agreement with the MG LO implementation.
  - The approach can help substantially to perform the next iteration of CMS/ATLAS searches/studies, given the intrinsic advantages of a reweighting method and the need of still larger MC samples in the future (Run3, for instance).

- The approach allows for easy extensions that are absent from current analyses:
  - s-dependent/different widths
  - adding b-quark in the ggH loop
  - alternative expressions of loop contributions from other BSM models

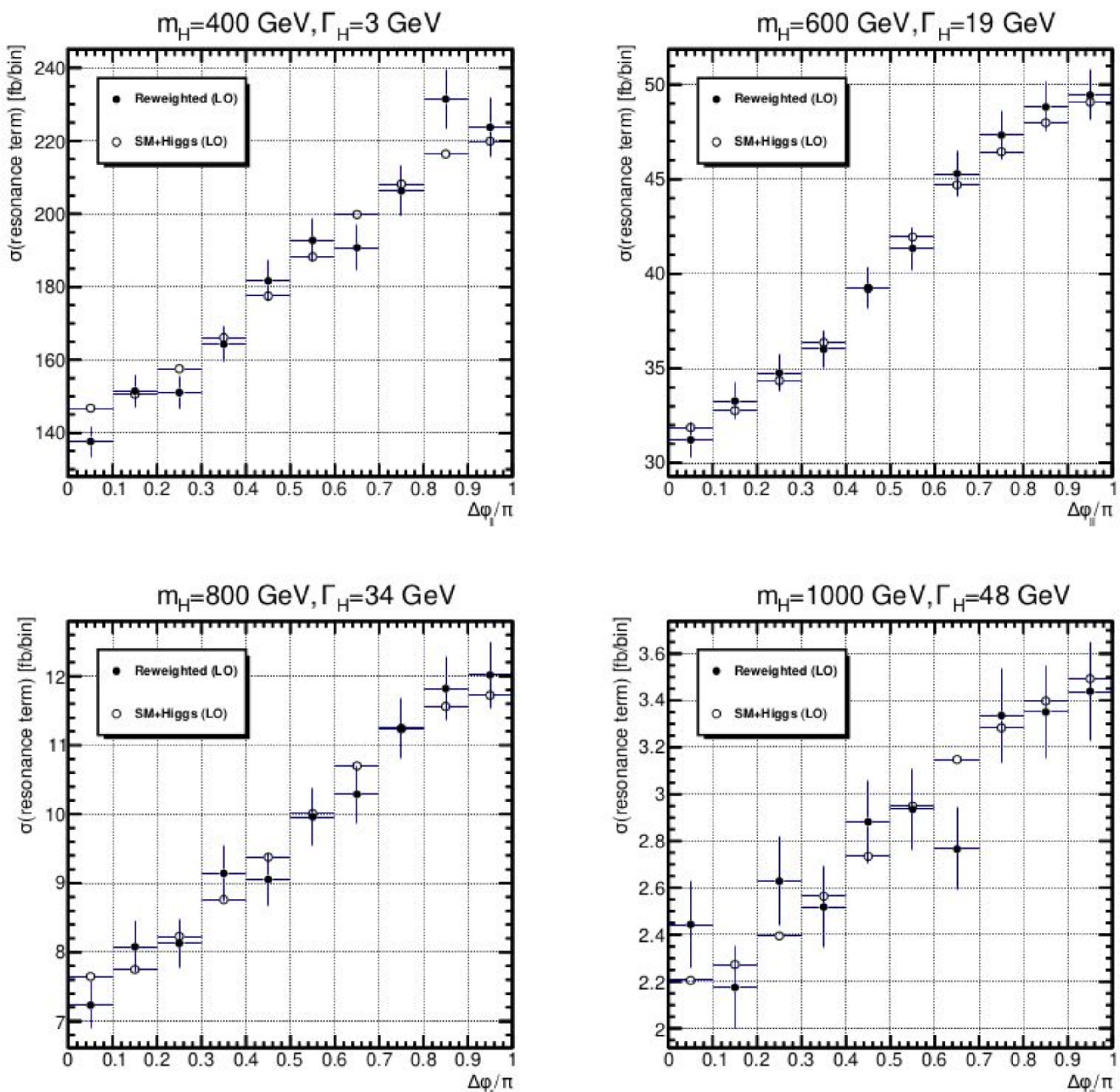
- It can also be applied in a simple way to NLO-generated pp→ttbar samples:
  - It absorbs a large fraction of NLO QCD corrections in an implicit way.
  - Difficult to determine the precision of this LO-like NLO reweighting approach, because no full NLO generator is available at the moment
  - Nevertheless the approach could even allow simple k-factor corrections tunes to reproduce NLO calculations, once these get available

Backup

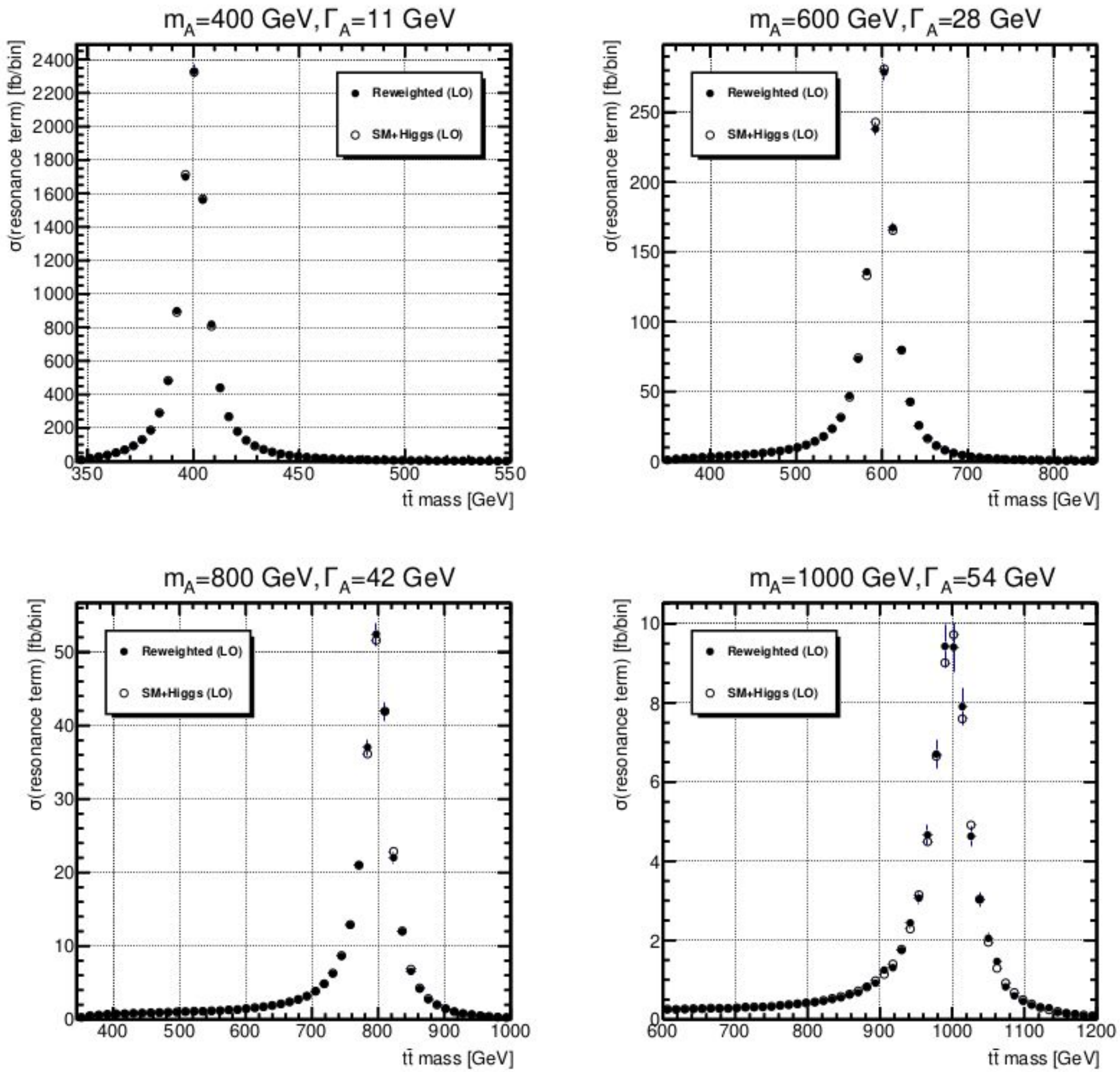
Validation: resonant terms, H case



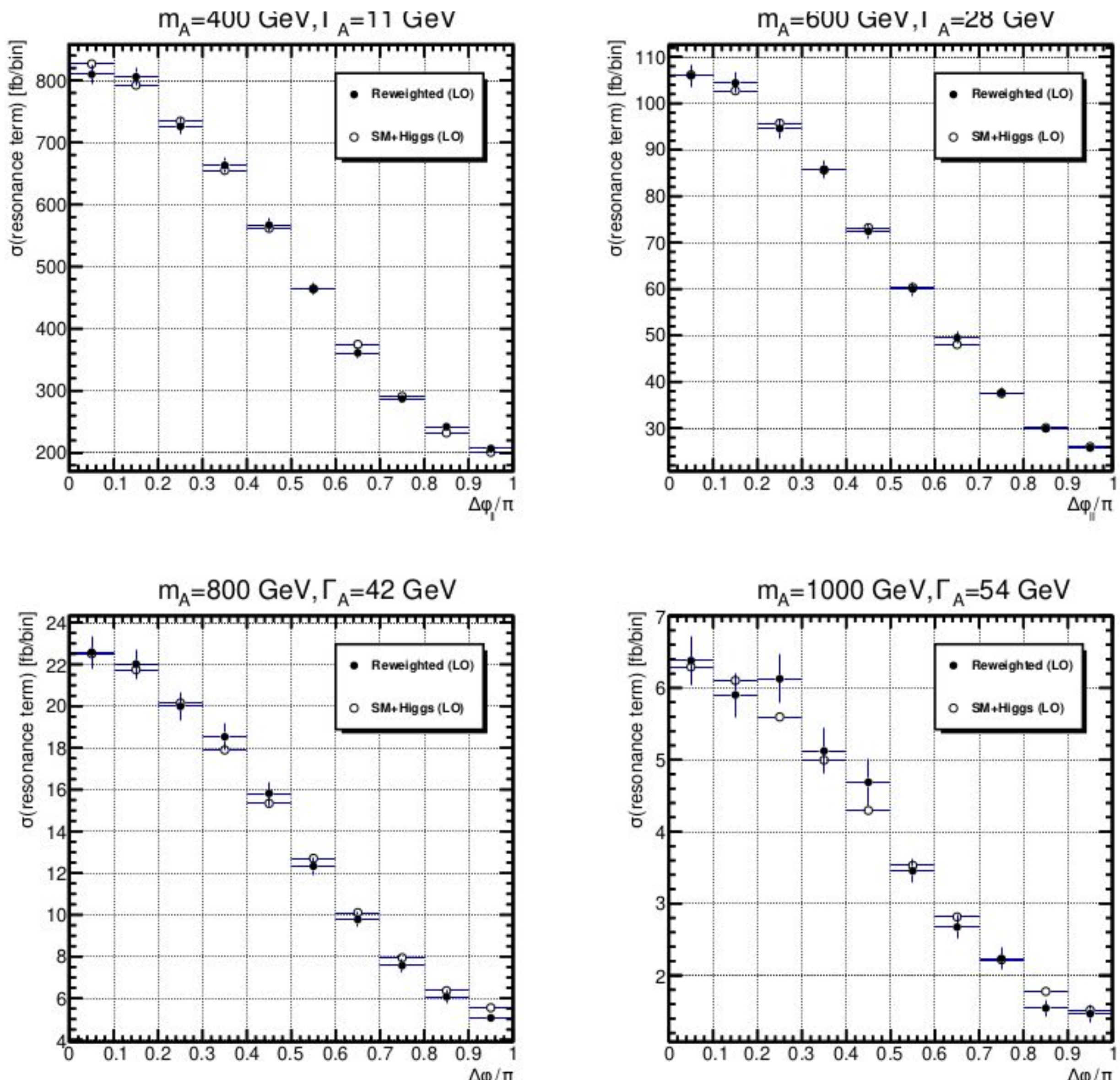
Validation: resonant terms, H case



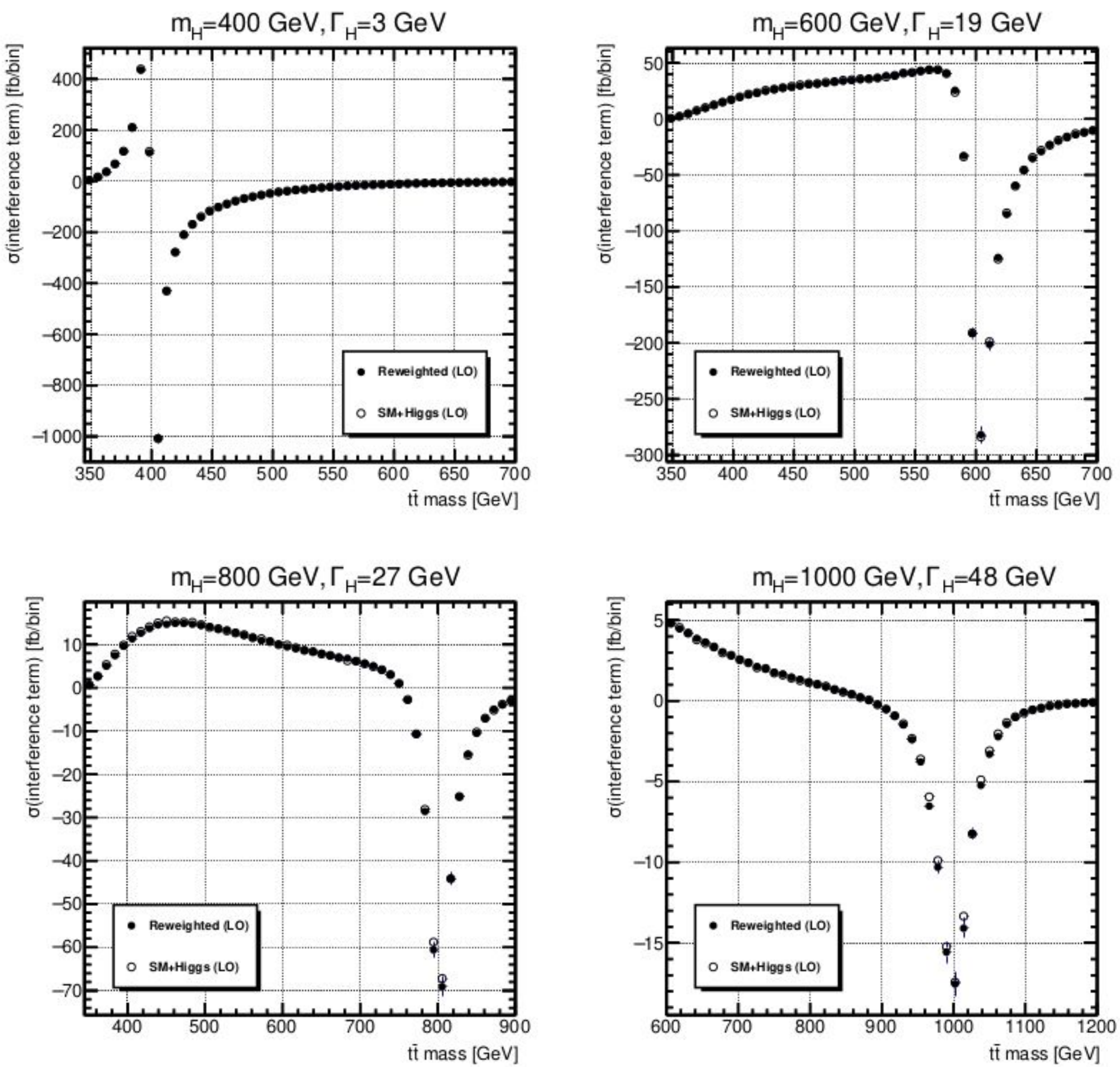
Validation: resonant terms, A case



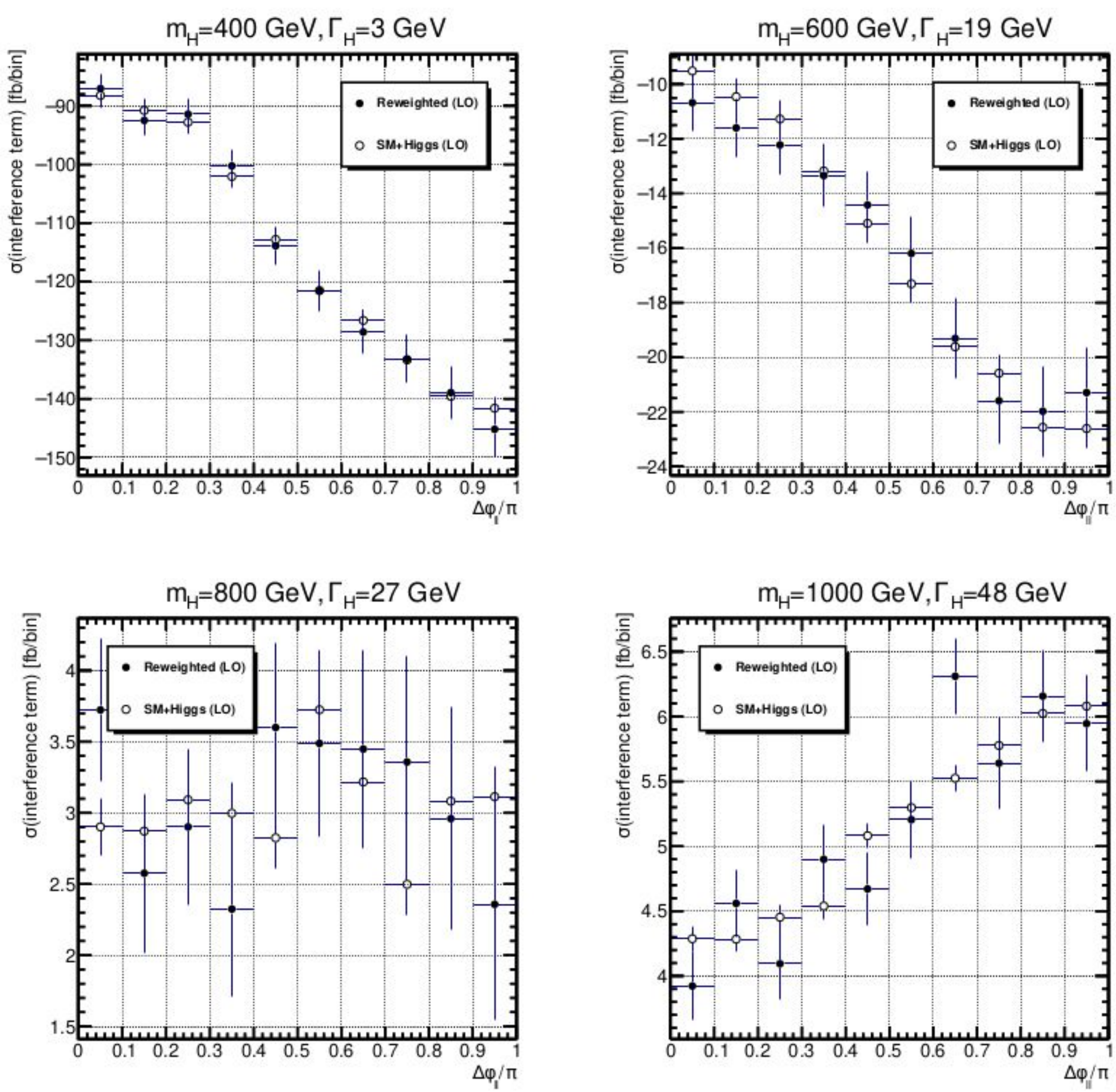
Validation: resonant terms, A case



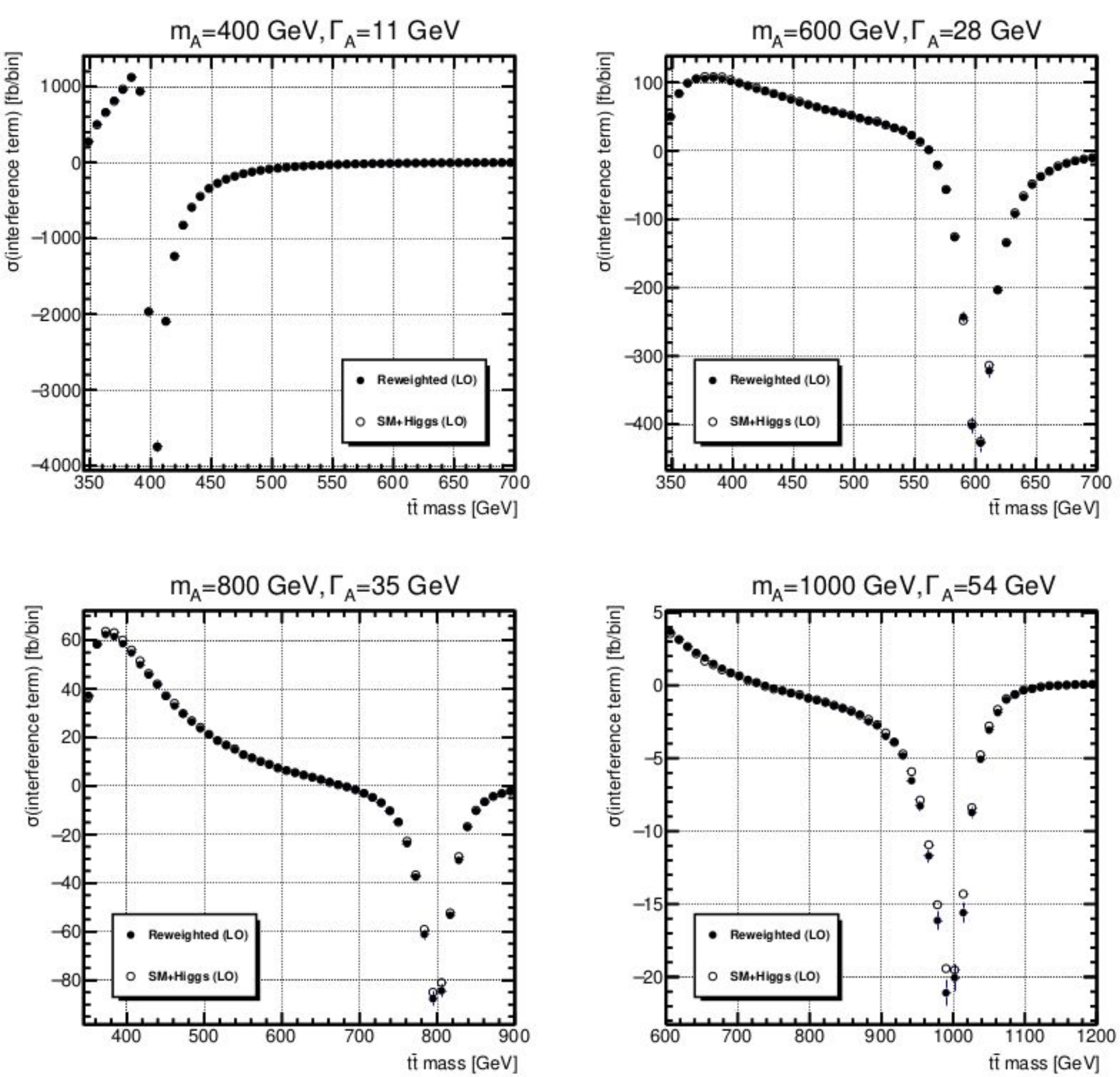
Validation: interference terms, H case



Validation: interference terms, H case



Validation: interference terms, A case



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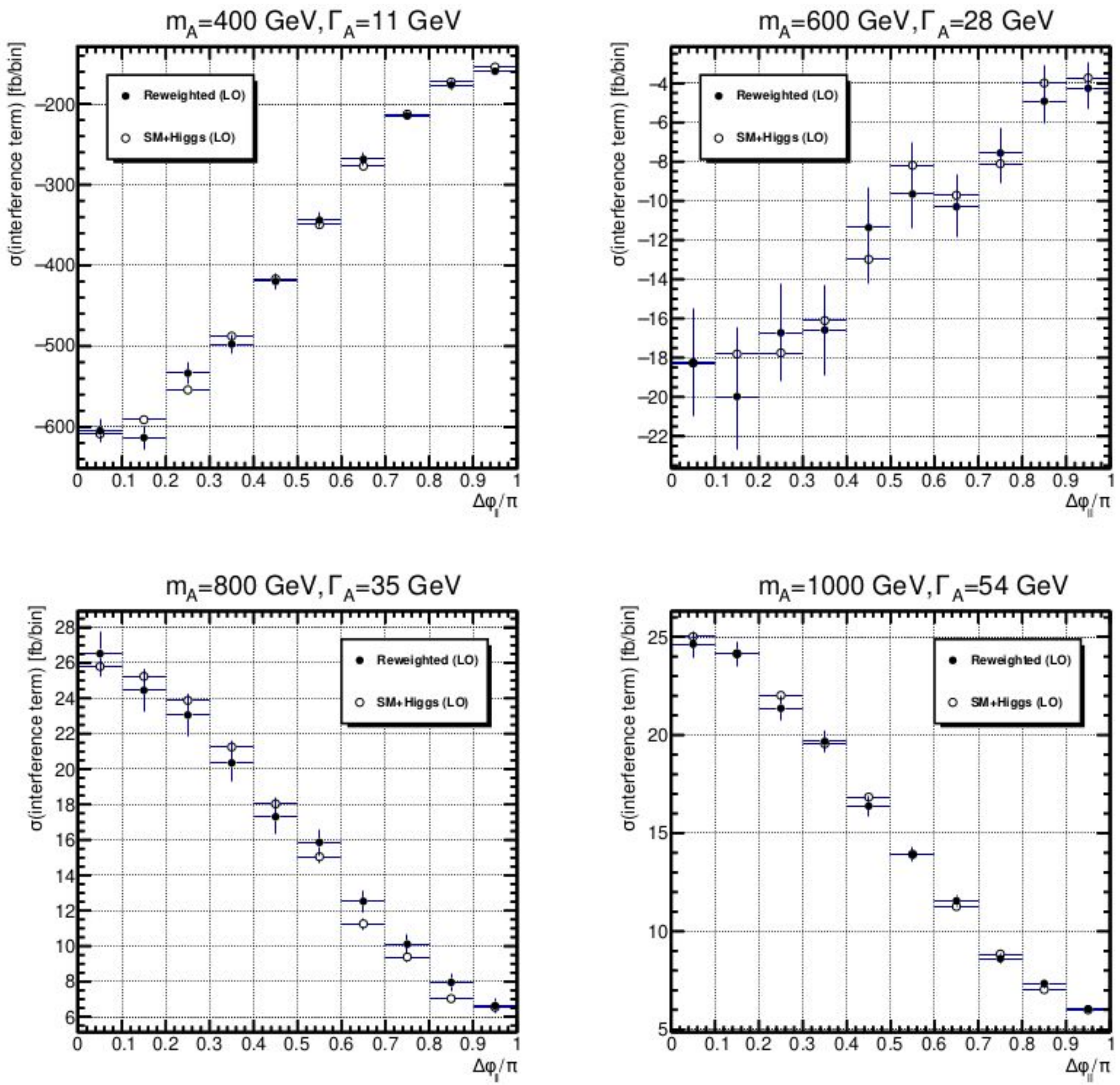
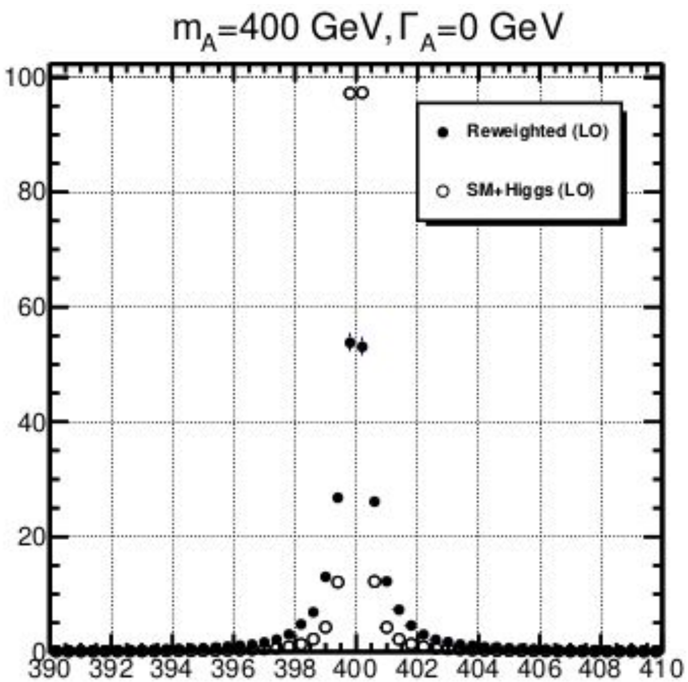
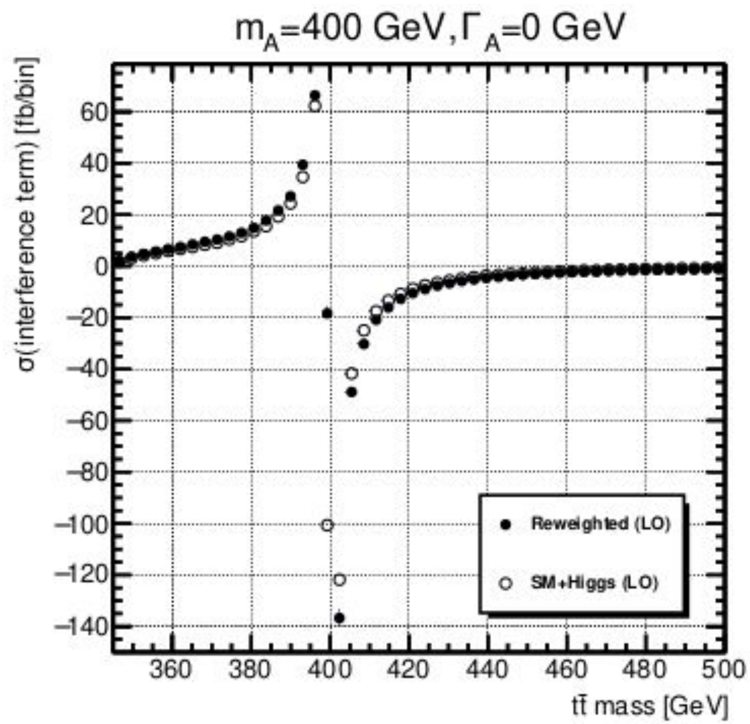
Validation: interference terms, A case



Adding b-quarks to ggH loop





y_t=0.15, 2HDM Higgs-aligned scenario

- The effect of the b-quark on the width is constant in this scenario: there is a cancellation of y_t effects in the partial width to b quarks
- Therefore the effect is only visible for relatively low values of the Higgs-top coupling, and relatively small Higgs masses (cross section decreases with y_t)
- Again, spin correlations are basically unaffected by the inclusion of this effect

Reweighting an NLO MC (aMC@NLO)

- **We have applied an LO-like reweighting to 1 million SM events pp->ttbar generated wtih aMC@NLO**
- **We have compared the differential shapes of "LO" and "LO-like NLO reweighting". NLO and LO cross sections are significantly different, so we have imposed a common normalization in this comparison.**
- **From the comparison, it is evident that the two variables under study (ttbar mass and deltaPhi) are almost unaffected. However, the distribution of variables like the polar angle of top production are visibly different in many case, as more or less expected (because ithis also happens for SM ttbar alone in the LO->NLO transition).**