Heavy scalar decay to top pairs at NLO in the EFT

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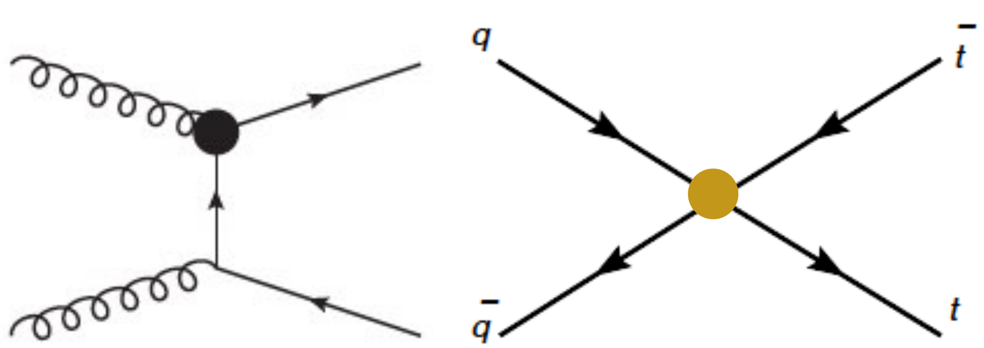
New physics in top pair production

No new light states

SMEFT: Dimension-6 operators

$$\mathcal{L}_{\text{Eff}} = \mathcal{L}_{\text{SM}} + \sum_i \frac{C_i^{(6)} O_i^{(6)}}{\Lambda^2} + \mathcal{O}(\Lambda^{-4})$$



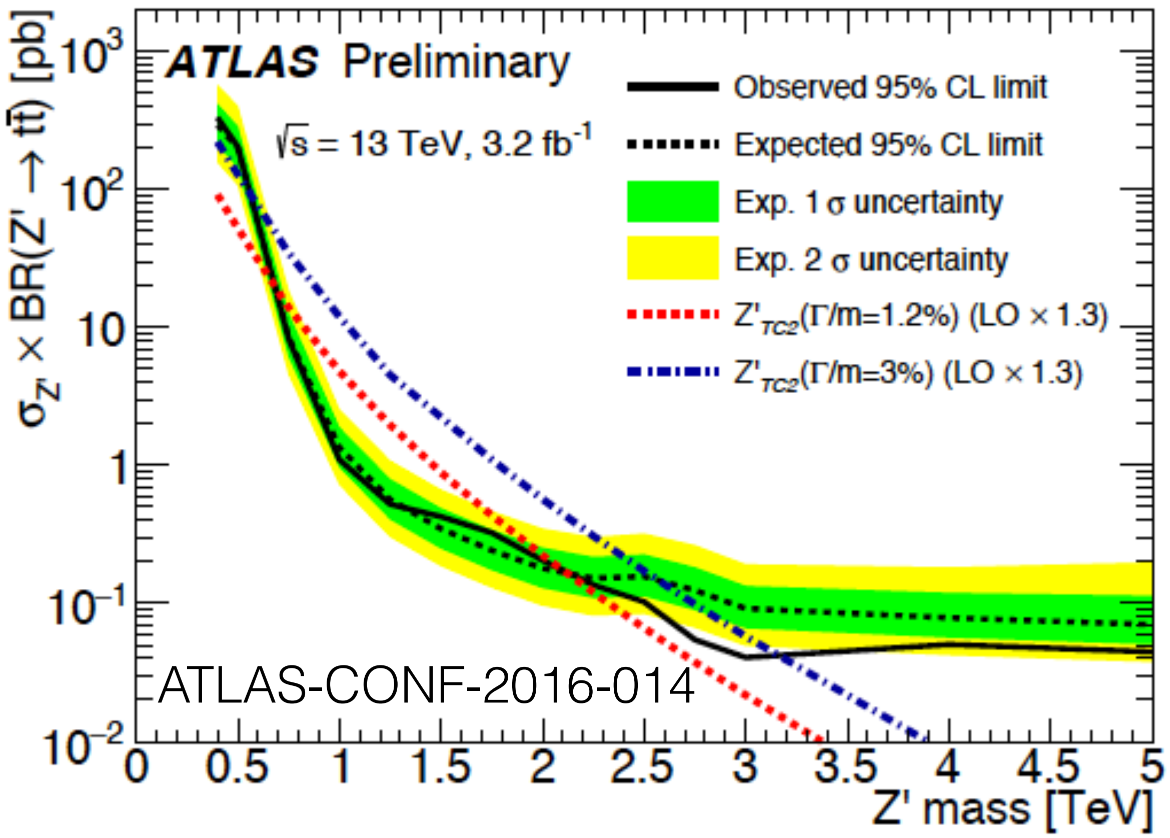
Typically deviations in the m_{tt} tails

New particles: Top resonances

A wide range of possibilities

- Spin 0 colour singlet
  - SUSY, 2HDM
- Spin 0 colour octet
  - MFV models
- Spin 1 colour singlet
  - Z'
- Spin 1 colour octet
  - KK gluons, colorons, axigluons
- Spin 2 colour singlet
  - Gravitons

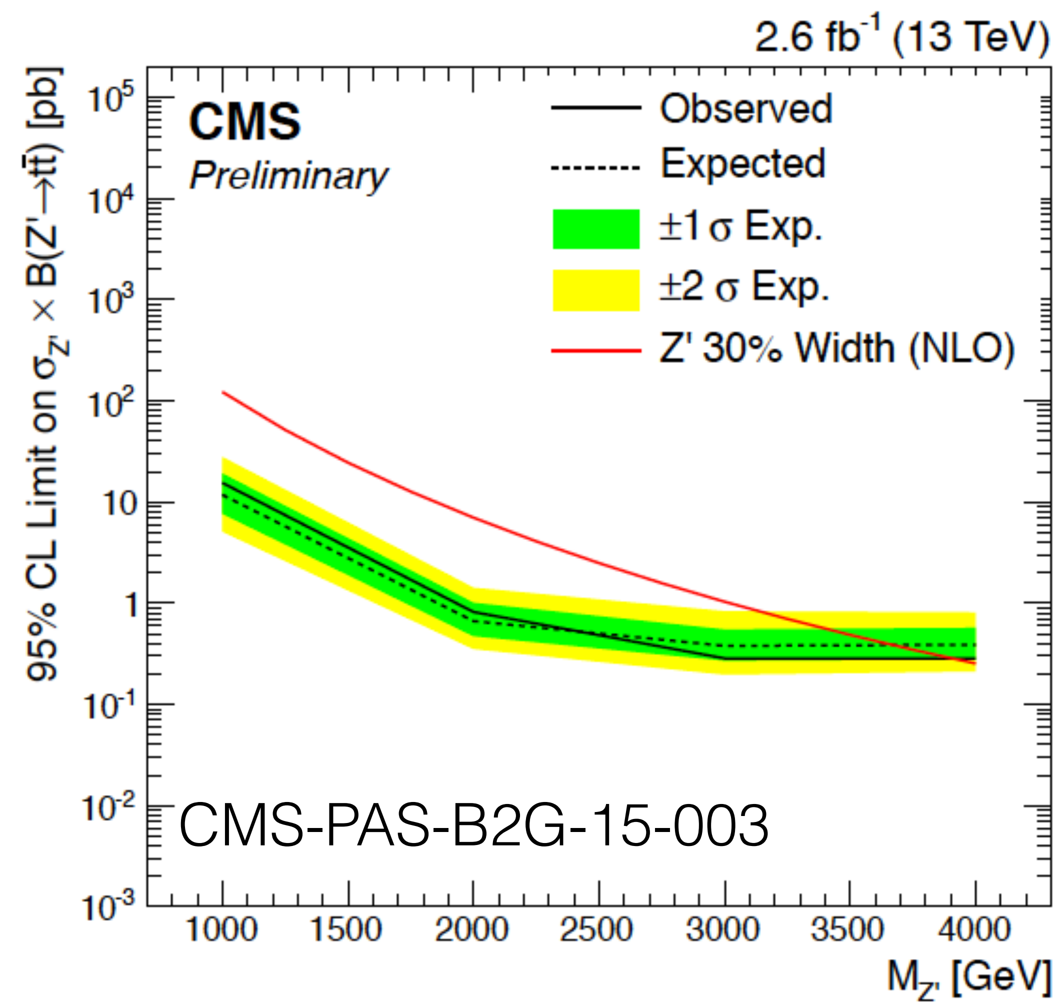
LHC searches for resonances



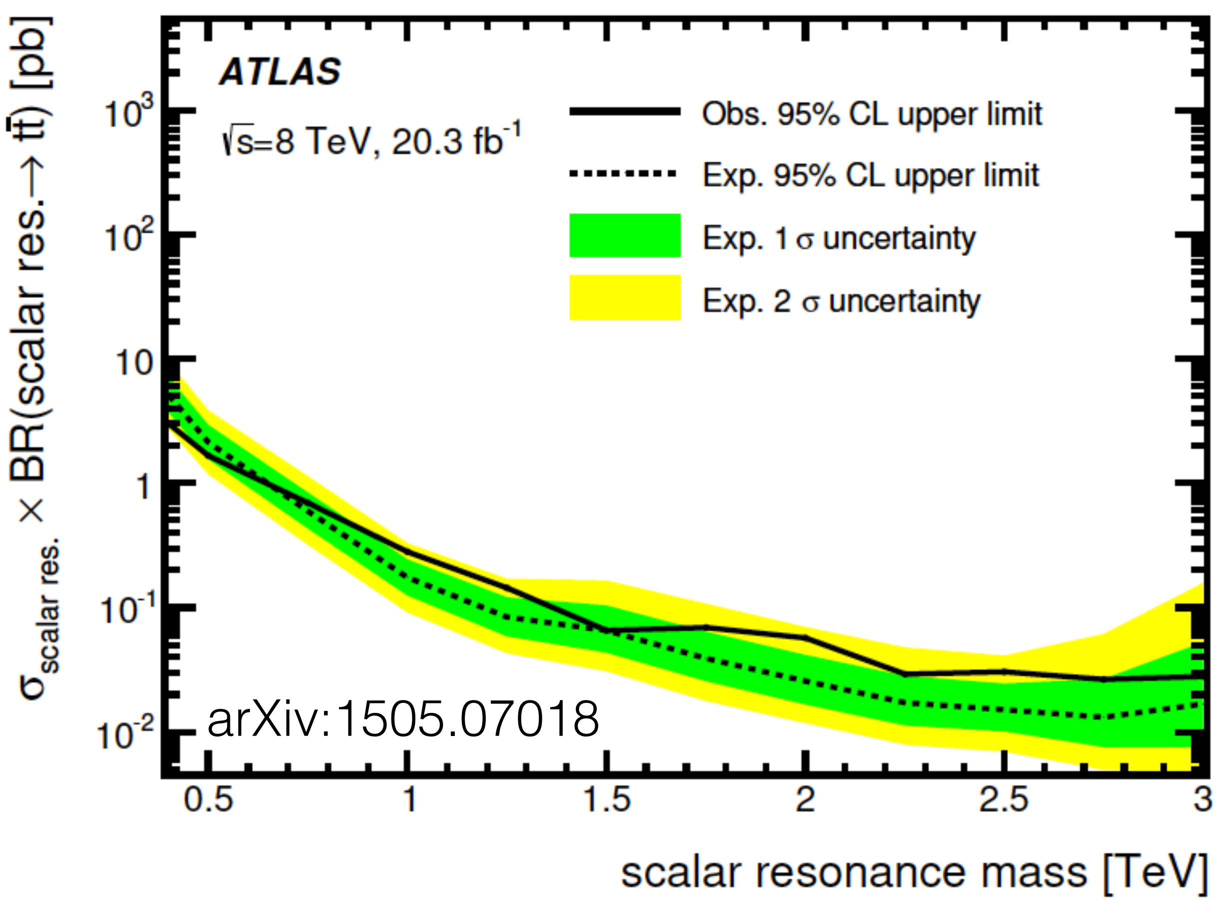
ATLAS-CONF-2016-014

ATLAS and CMS searches:

- Resolved (low mass)
- Boosted (high mass)



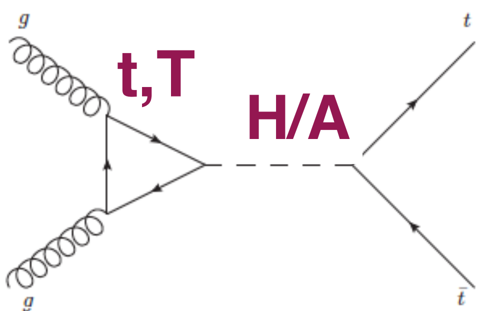
CMS-PAS-B2G-15-003



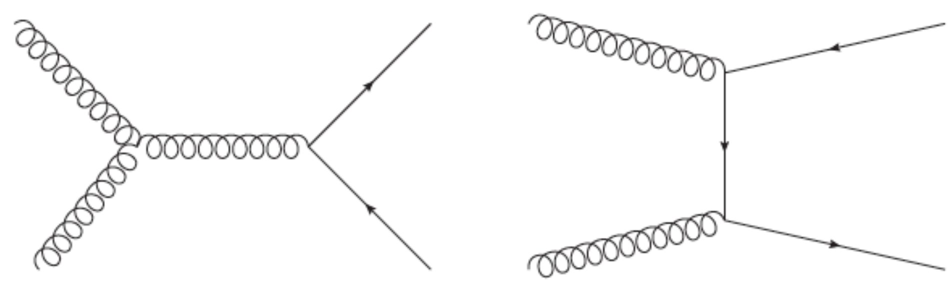
arXiv:1505.07018

+KK-gluon and 2HDM interpretations
ATLAS-CONF-2016-073

Scalar resonances in $t\bar{t}$



signal

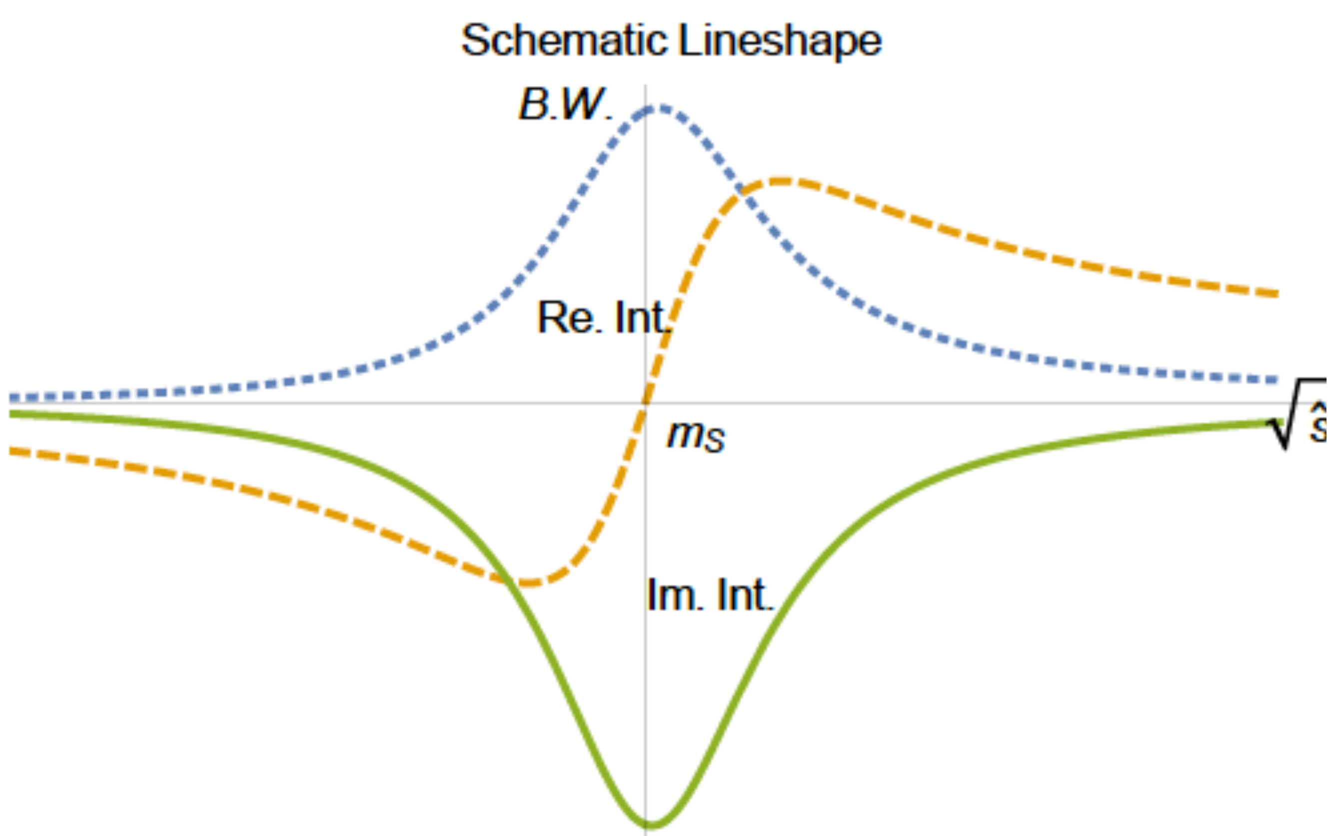


QCD continuum

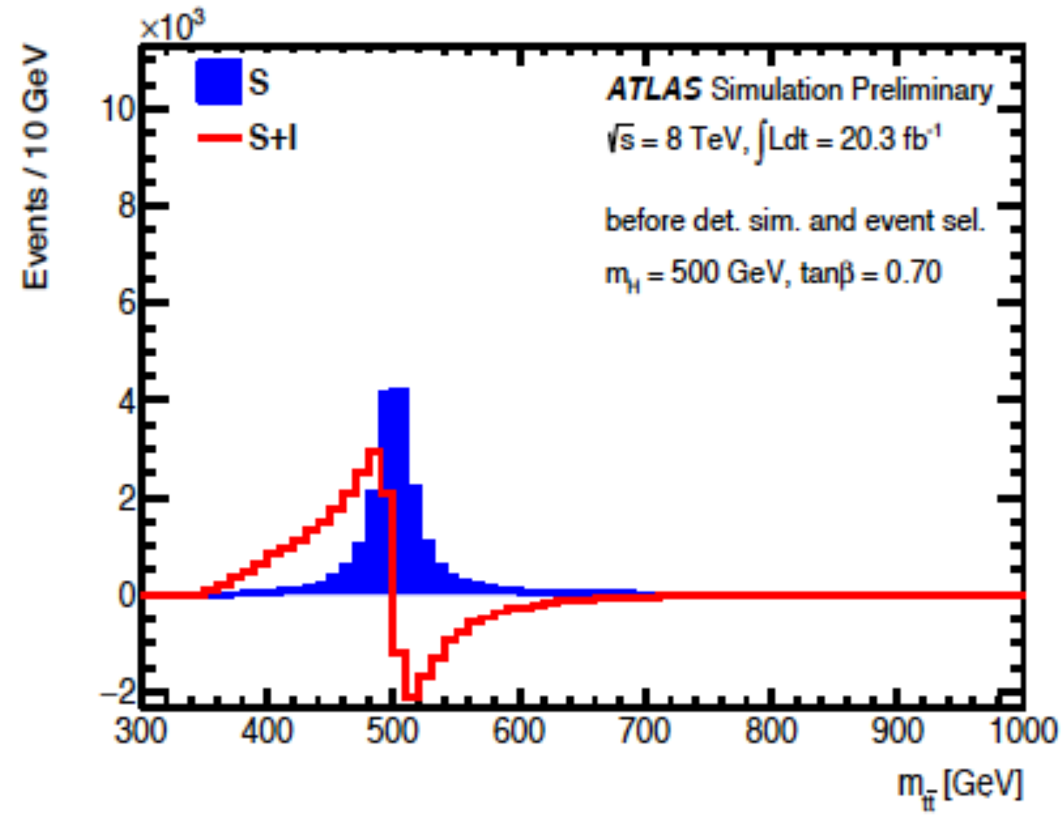
Interference important for the line shape for widths~0.01M

Peak-dip structures

Scalar or pseudoscalar resonance
Top-loop, heavy quark (VLQ) loop

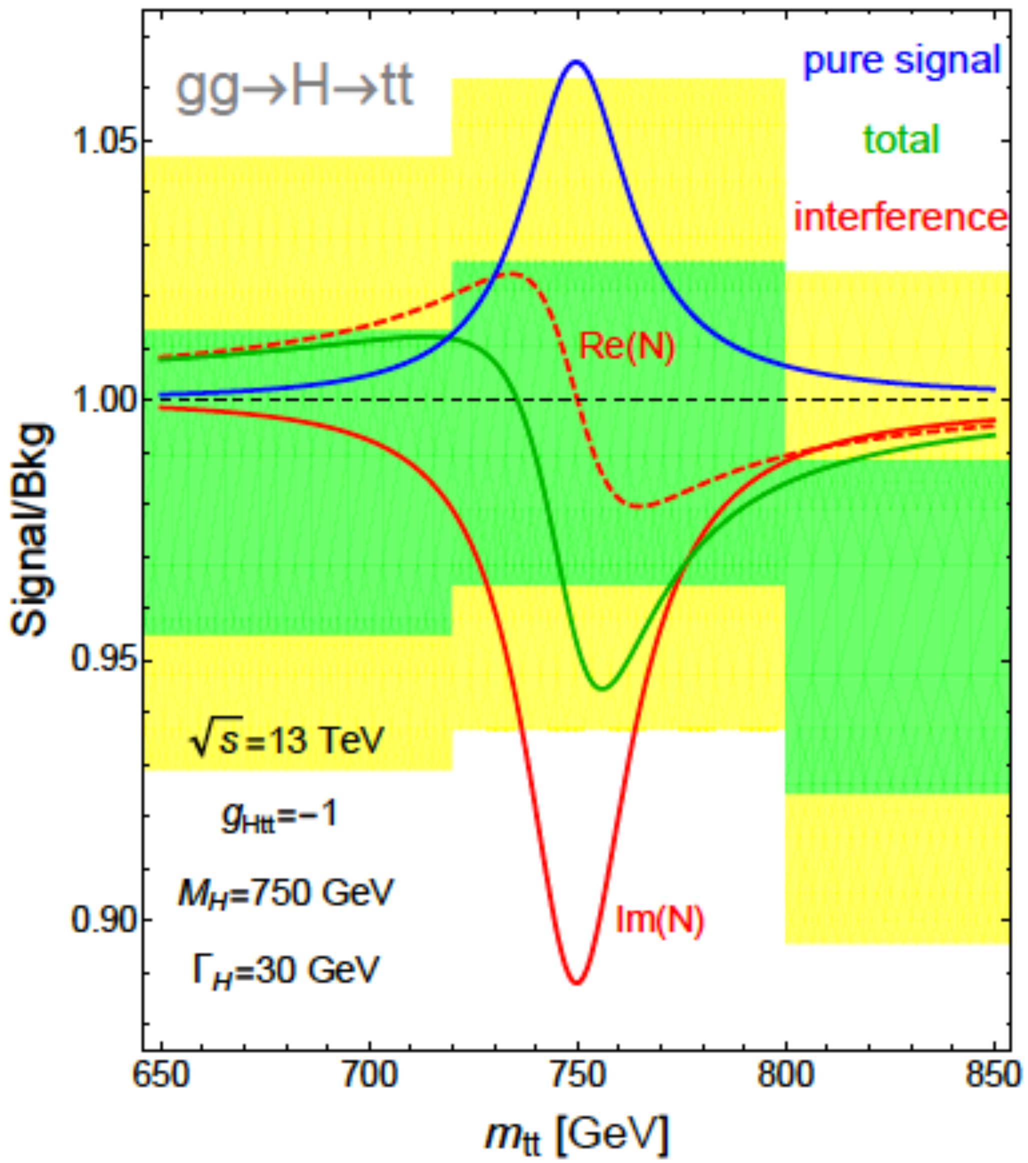


Carena, Liu arXiv: 1608.07282

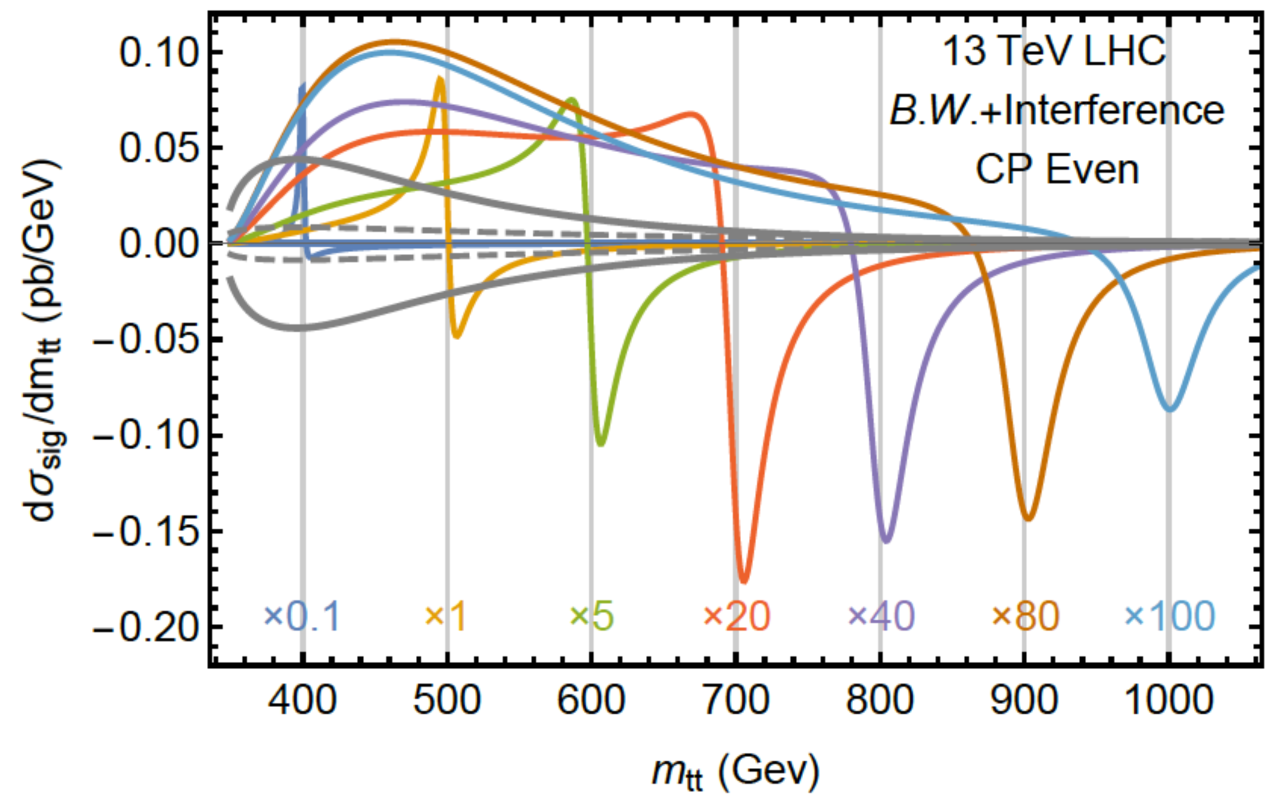


ATLAS-CONF-2016-073
First experimental study including the interference

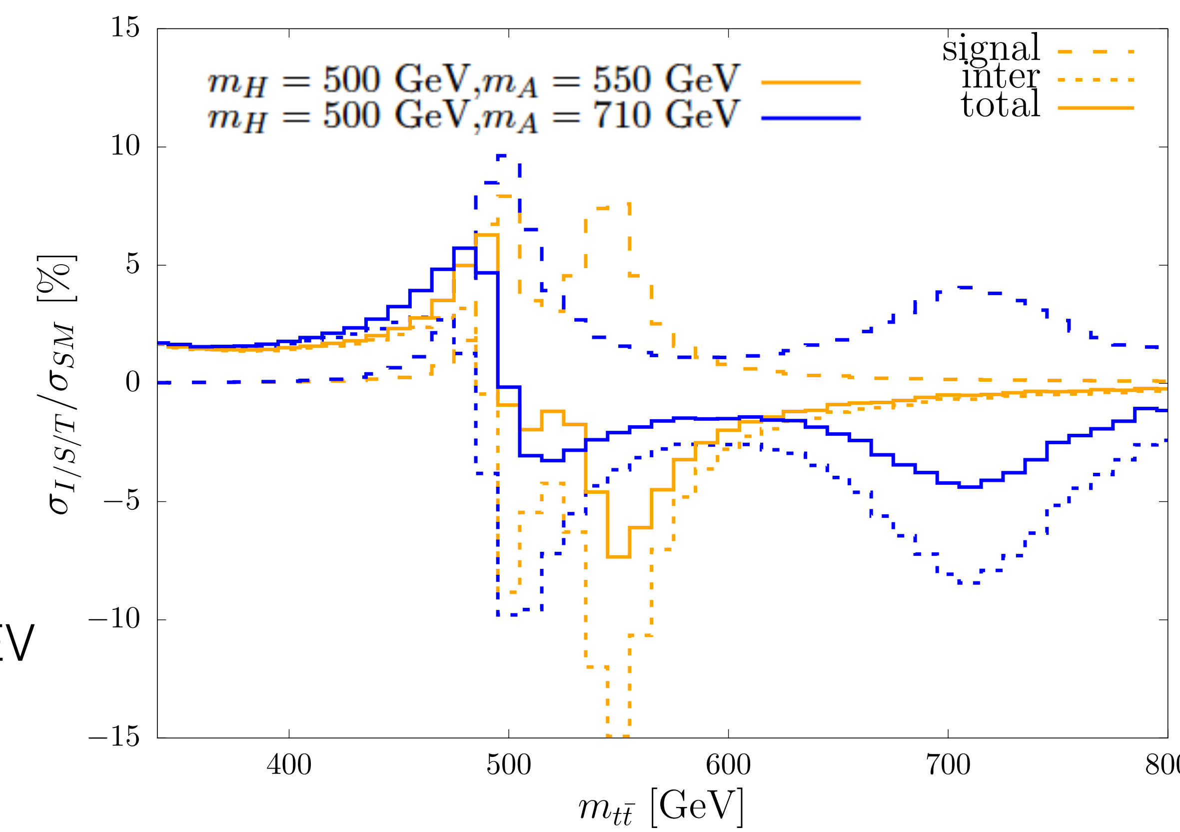
Line-shapes



Ellis, Djouadi, Quevillon arXiv:1605.00542



Carena, Liu arXiv: 1608.07282



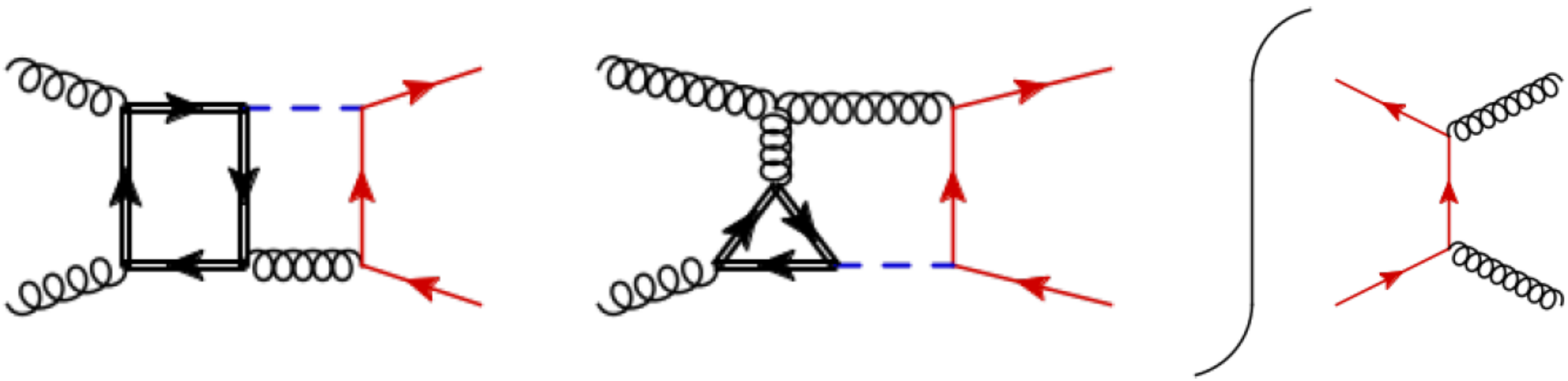
Hespel, Maltoni, EV
arXiv:1606.04149

Precise description of the line shapes

- Interference: crucial for a realistic description of the line shape (in particular for a gluon initiated scalar resonance)
- Experiments moving towards including this interference: optimised experimental strategies beyond Breit-Wigner ATLAS-CONF-2016-073
- Need for precise predictions:
  - Background: NNLO Czakon, Mitov et al arXiv:1601.05375, 1606.03350
  - Signal: NLO (higgs production and decay into heavy quarks)
  - Interference: LO + NLO approximation
    K-factor approximation: Hespel, Maltoni, EV arXiv:1606.04149
    Soft-gluon approximation: Bernreuther et al. arXiv:1511.0558

Interference beyond LO

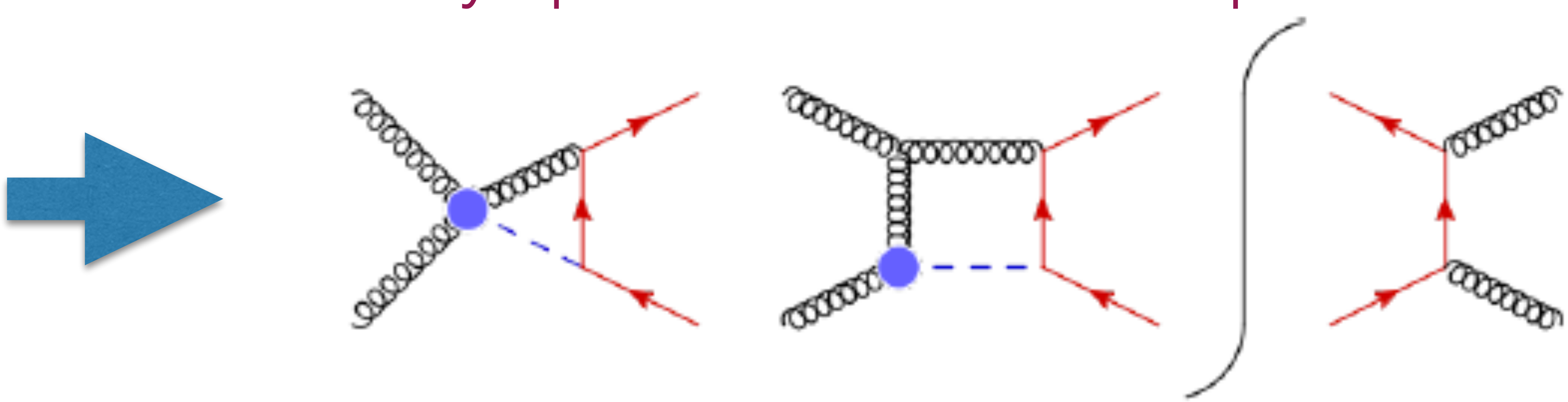
Non-factorisable corrections



Very hard multi-scale integrals

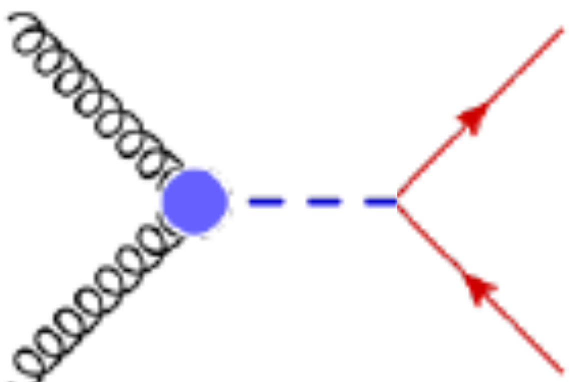
- Vanishing for Signal@NLO
- Relevant for interference

What if a heavy quark runs in the loop? EFT limit

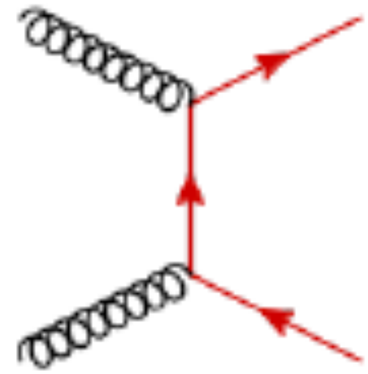


2-loop becomes 1-loop

$gg \to H(A) \to t\bar{t}$ in the EFT



Signal

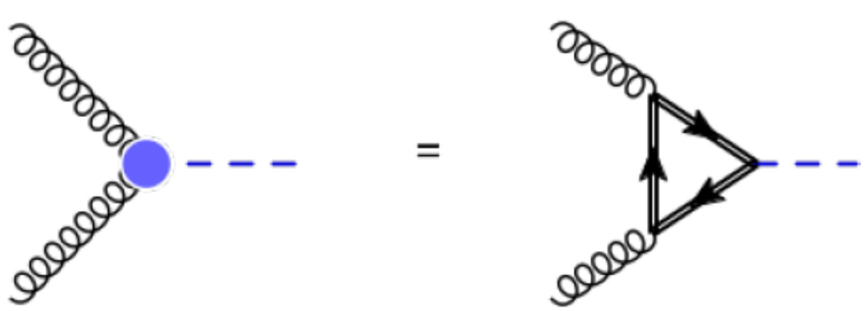


Background

Exact for heavy VLQ running in the loop

$$\boxed{O_{HG} = g_s^2 G^A_{\mu\nu} G^{A\mu\nu} H}$$ and/or $$\boxed{O_{A\tilde{G}} = g_s^2 G^A_{\mu\nu} \tilde{G}^{A\mu\nu} A}$$

Operator coefficient can be matched to UV theory



$$\frac{C_{HG}(m_F)}{\Lambda} = -\frac{y_F}{48\pi^2 m_F}$$
$$\frac{C_{A\tilde{G}}(m_F)}{\Lambda} = -\frac{\tilde{y}_F}{32\pi^2 m_F}$$

For a VLQ coupling to a scalar

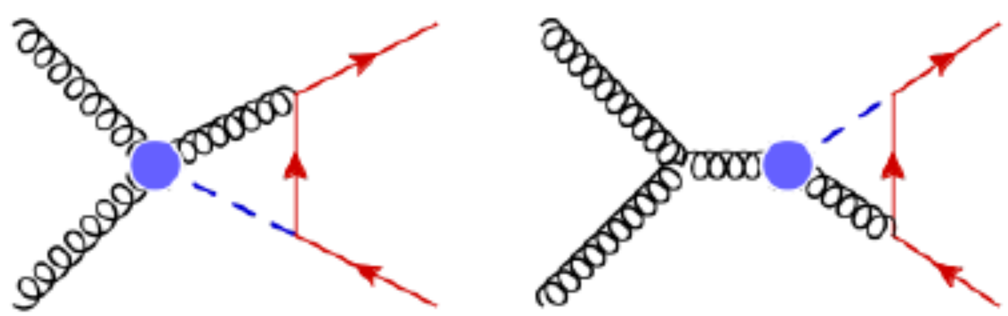
$$L_{Yuk} = y_F \bar{F} F H + \tilde{y}_F F i\gamma^5 F A$$

$gg \to H(A) \to t\bar{t}$ at NLO in the EFT

Effective Lagrangian $$L_{Eff} = L_{SM} + y_t \bar{t} t H + \tilde{y}_t \bar{t} i \gamma^5 t A + \frac{C_{HG}}{\Lambda} O_{HG} + \frac{C_{A\tilde{G}}}{\Lambda} O_{A\tilde{G}}$$

Not renormalisable on its own

At NLO



UV divergent diagrams

O_{HG} mixes into $$O_{tG} = g_s y_t \bar{t} \sigma^{\mu\nu} T^A t G^A_{\mu\nu}$$

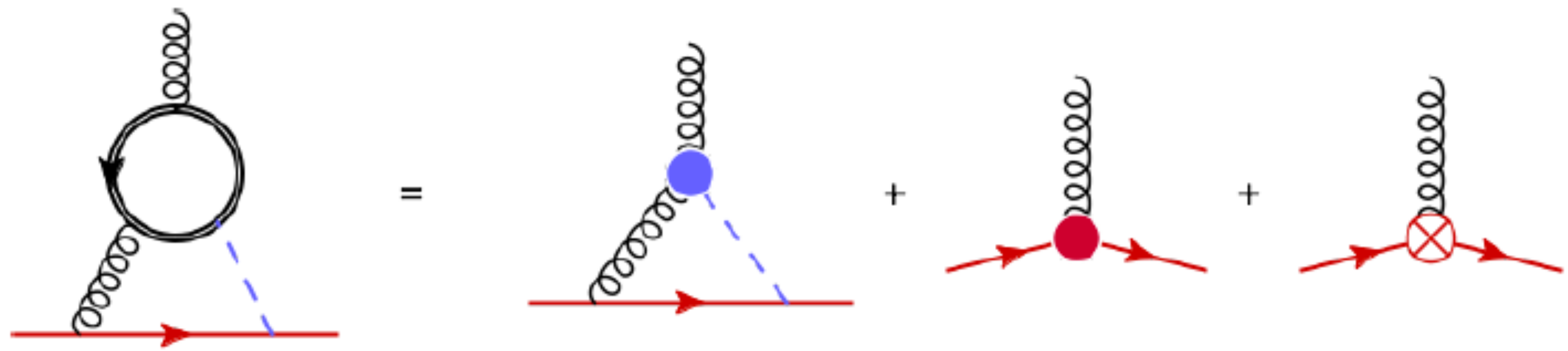
→ Needs to be added to the theory

$$C_{tG} \to C^{(0)}_{tG} = Z_{tG,i} C_i$$

$$Z_{tG,HG} = -\frac{\alpha_s}{2\pi} \epsilon^{-1}_{UV}$$

to cancel the UV poles

Matching for O_{tG}



Barr-Zee diagram

Computed in the context of lepton dipole moments as an $1/m_F$ expansion: Altmannshofer et al arXiv:1503.04830

$$\frac{C_{HG}(m_F)}{\Lambda} = -\frac{y_F}{48\pi^2 m_F} - \frac{11\alpha_s y_F}{192\pi^3 m_F} + \mathcal{O}(\alpha_s^2)$$

$$\frac{C_{A\tilde{G}}(m_F)}{\Lambda} = -\frac{\tilde{y}_F}{32\pi^2 m_F} + \mathcal{O}(\alpha_s^2)$$

$$\frac{C_{tG}(m_F)}{\Lambda} = -\frac{\alpha_s}{1152\pi^3 m_F}\left(8y_F - 9\tilde{y}_F\frac{\tilde{y}_t}{y_t}\right) + \mathcal{O}(\alpha_s^2)$$

To compute at $Q=m_{H/A}/2$

$$\frac{C_i(\mu)}{d\log\mu} = \frac{\alpha_s(\mu)}{\pi}\gamma_{ij}C_j(\mu)$$

$$\gamma = \begin{pmatrix} 0 & 0 & 0 \\ 0 & 0 & 0 \\ -1 & \tilde{y}_t/y_t & 1/3 \end{pmatrix}$$

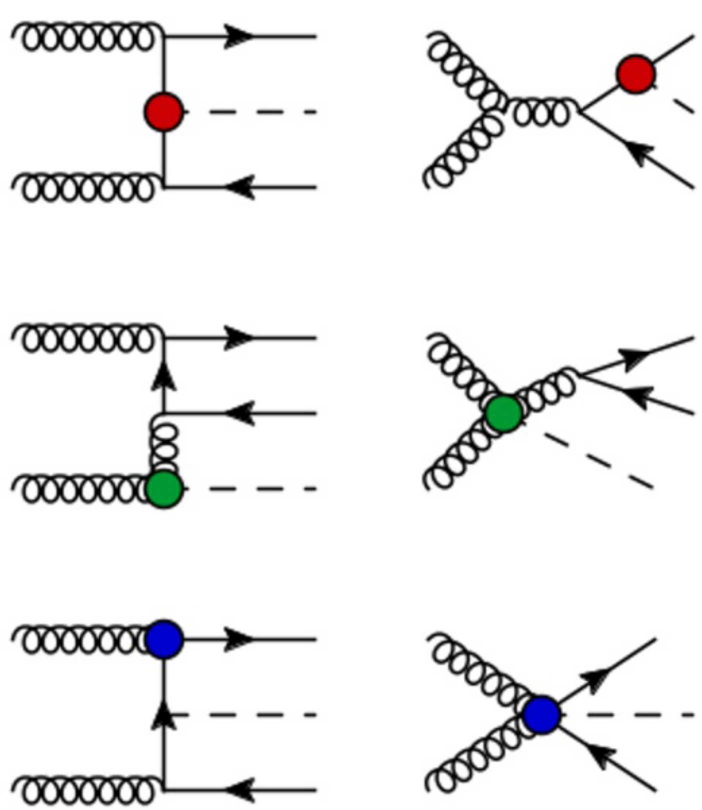
Matching (two-loop ggH and Barr-Zee) Running: RG equations

Alonso et al. arxiv:1312.2014

NLO implementation

After matching: a NLO EFT calculation in MG5_aMC@NLO:
Similar implementation to:

- top pair production: Franzosi and Zhang (arxiv:1503.08841)
- single top production: C. Zhang (arxiv:1601.06163)
- ttZ/γ, gg>HZ: O. Bylund, F. Maltoni, I. Tsinikos, EV, C. Zhang (arXiv:1601.08193)
- ttH, H, Hj, HH: F. Maltoni, EV, C. Zhang (arXiv:1607.05330)



$$O_{t\phi} = y_t^3 \left(\phi^\dagger\phi\right) \left(\bar{Q}t\right) \tilde{\phi}$$
$$O_{\phi G} = y_t^2 \left(\phi^\dagger\phi\right) G^A_{\mu\nu} G^{A\mu\nu}$$
$$O_{tG} = y_t g_s (\bar{Q}\sigma^{\mu\nu} T^A t)\tilde{\phi} G^A_{\mu\nu}$$

Ingredients already exist

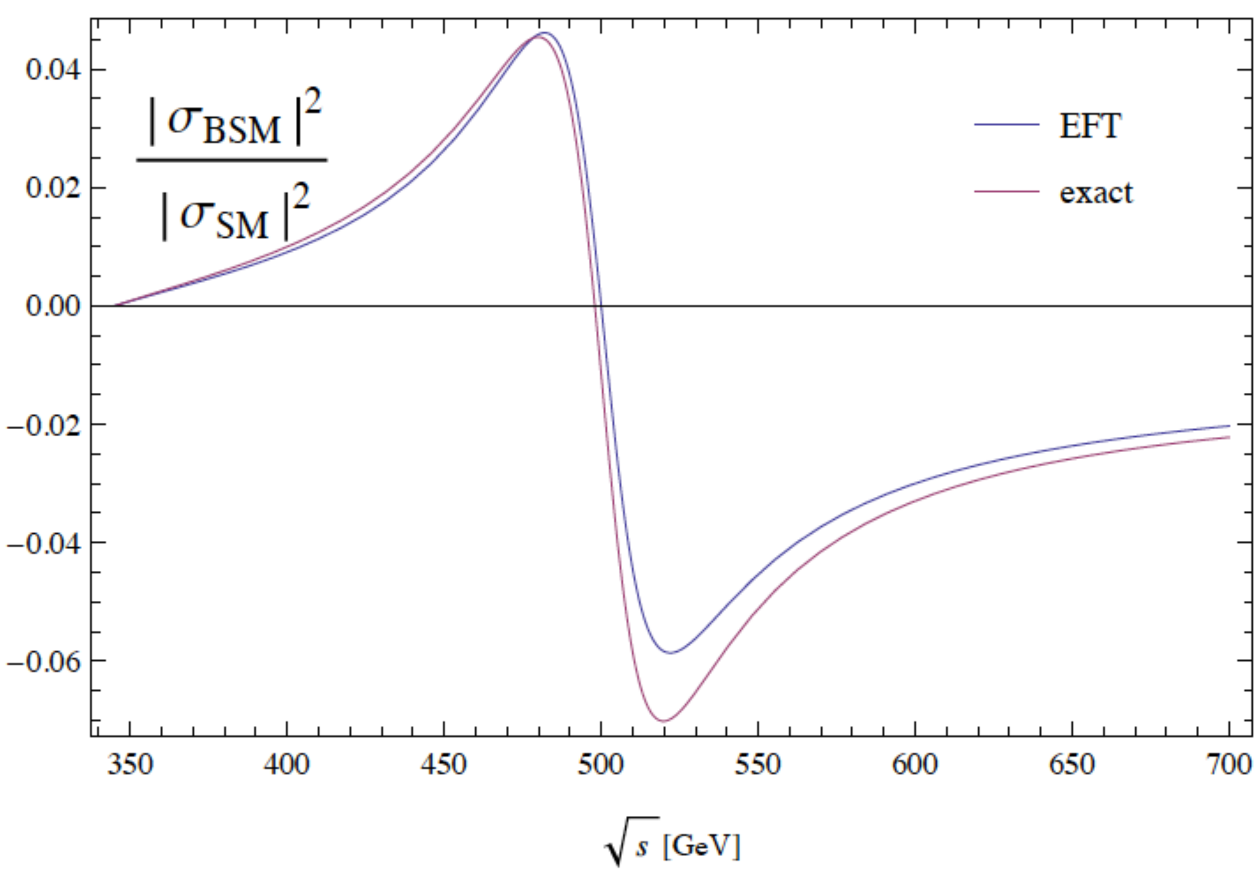
Results: Fixed order

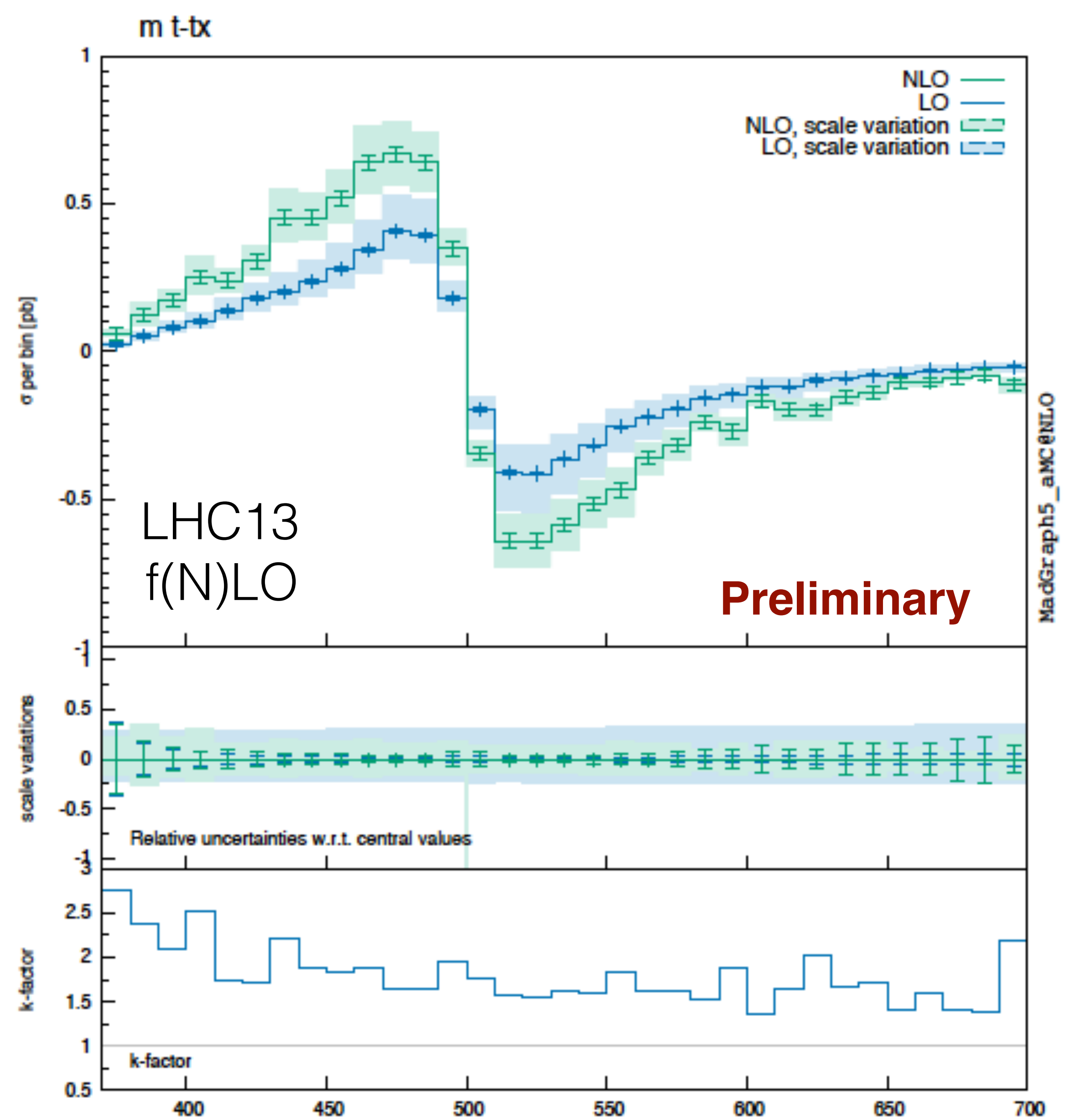
Scenario A: Heavy VLQ

m_H=500 GeV, Γ_H=40 GeV

m_F=500 GeV, y_F=5, y_t=0.4

$$\frac{C_{HG}}{\Lambda} = -5.11 \times 10^{-5}\ \text{GeV}^{-1}\,,$$
$$\frac{C_{tG}}{\Lambda} = -1.40 \times 10^{-6}\ \text{GeV}^{-1}\,.$$





EFT: a good approximation in this case

Dominated by VLQ loop

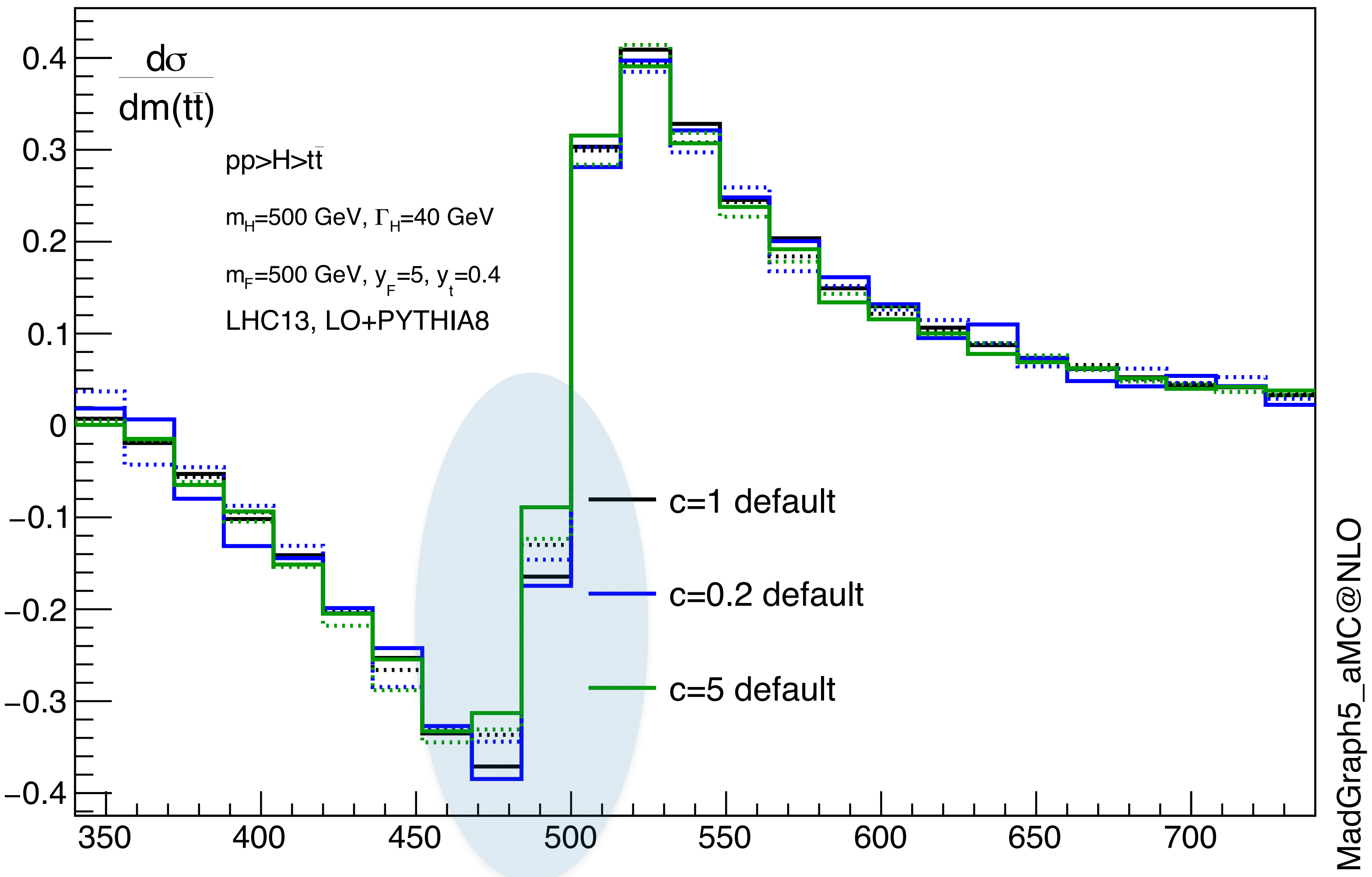
Matching to the PS: subtleties

- Resonance information in the event record: Shower instructed to preserve the reconstructed resonance mass
- Different shower evolution depending on the information in the event file even for the same final state kinematics
- The choice is an arbitrary one
- Procedure to determine whether information is recorded in MG5_aMC@NLO: Frederix et al 1603.01178
  - based on integration channel: Feynman diagram-based
  - for an s-channel resonance information written if

$$\left| m_\beta^{\mathrm{rec}} - m_\beta \right| < x_{\mathrm{cut}} \Gamma_\beta$$

  - Relevant information passed to MC counterterms

Matching to the PS (1)

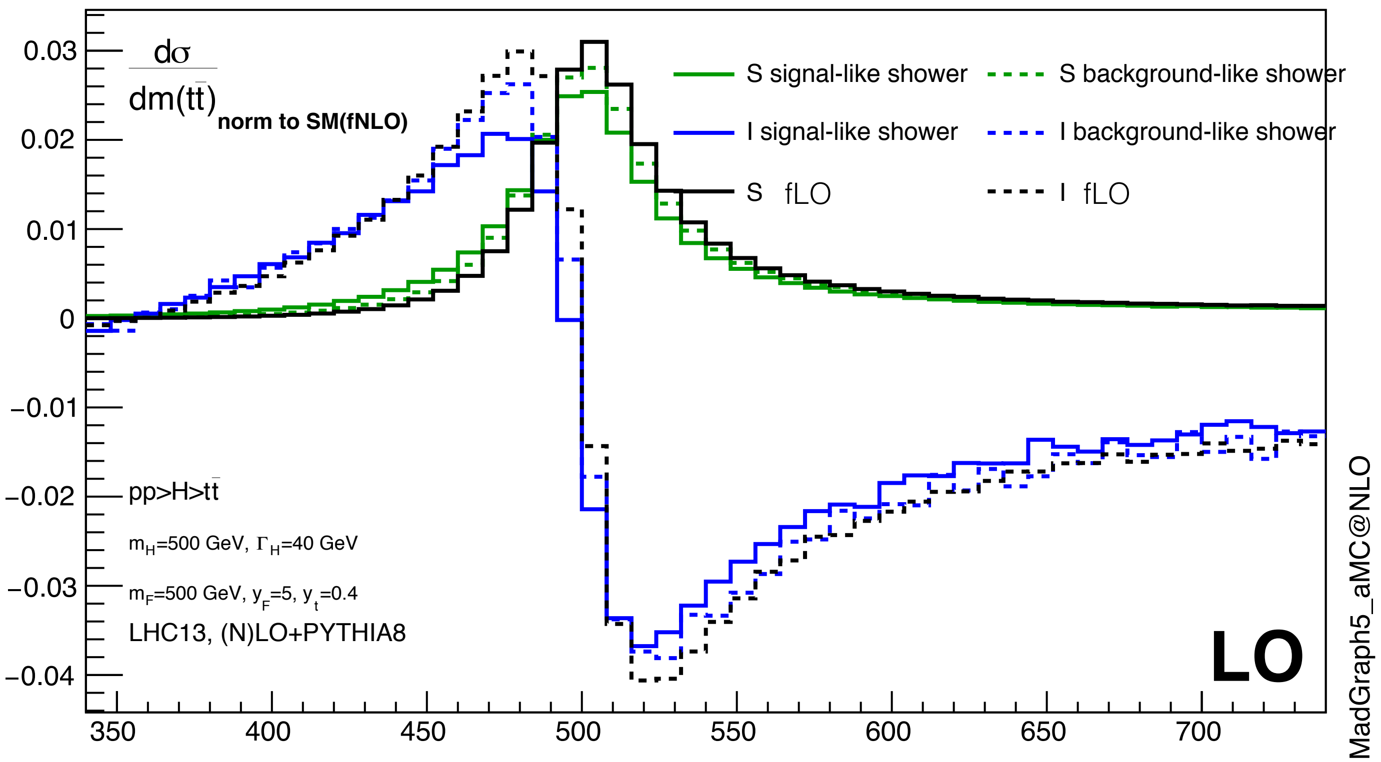


- Is there a meaningful way to compute the interference independently of c?
- In the context of EFT typically deviations are small
- Computation gives $B+cI+c^2S$
- To extract the interference use optimal c (plus/minus) and then rescale, but c is not an overall rescaling due to the shower

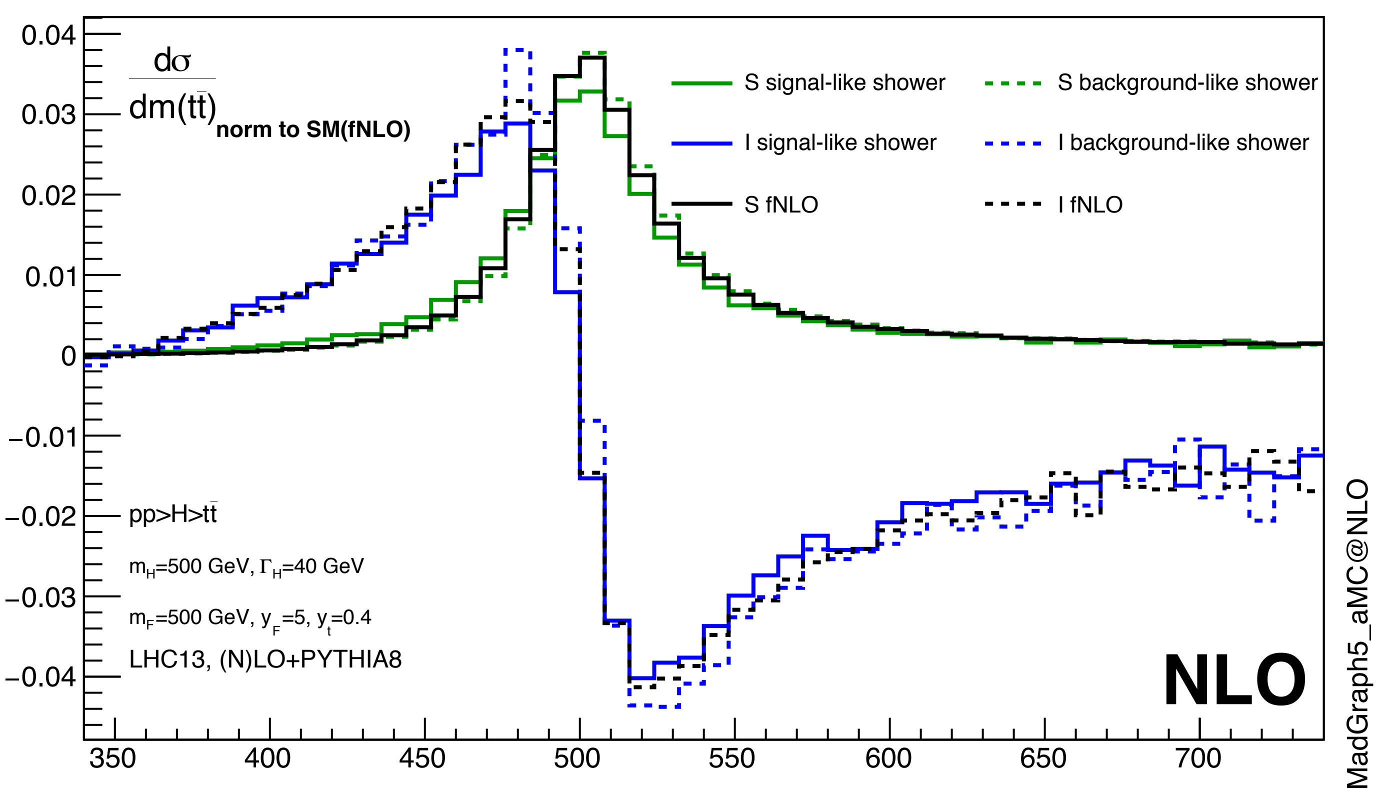
In this case we need to ensure our use of optimal c choice does not change the line shape

Is this even possible?

Matching to the PS (2)

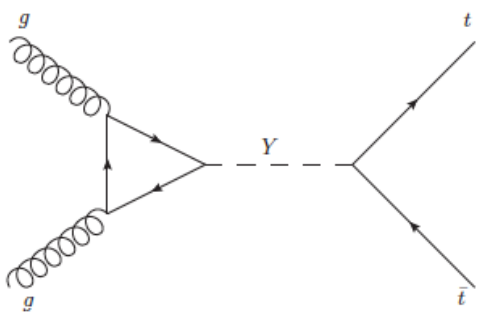


Preliminary



- How big is the difference between background (no resonance recorded) and signal-like showering (always recorded)? This can be large. Is this expected?
- Different behaviour at LO and NLO.
- Check for consistency and code modifications

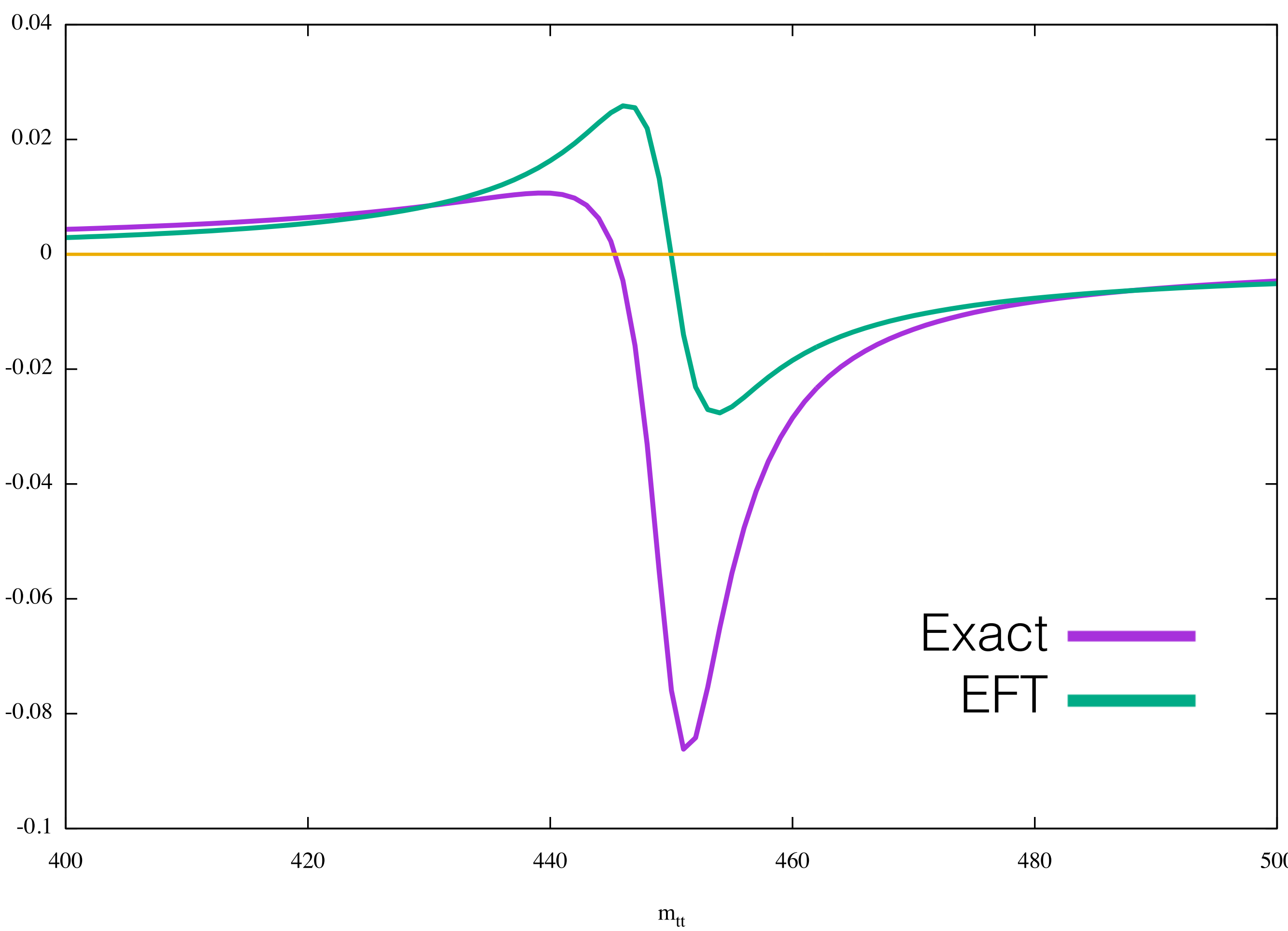
Top-loop induced scenarios: 2HDM

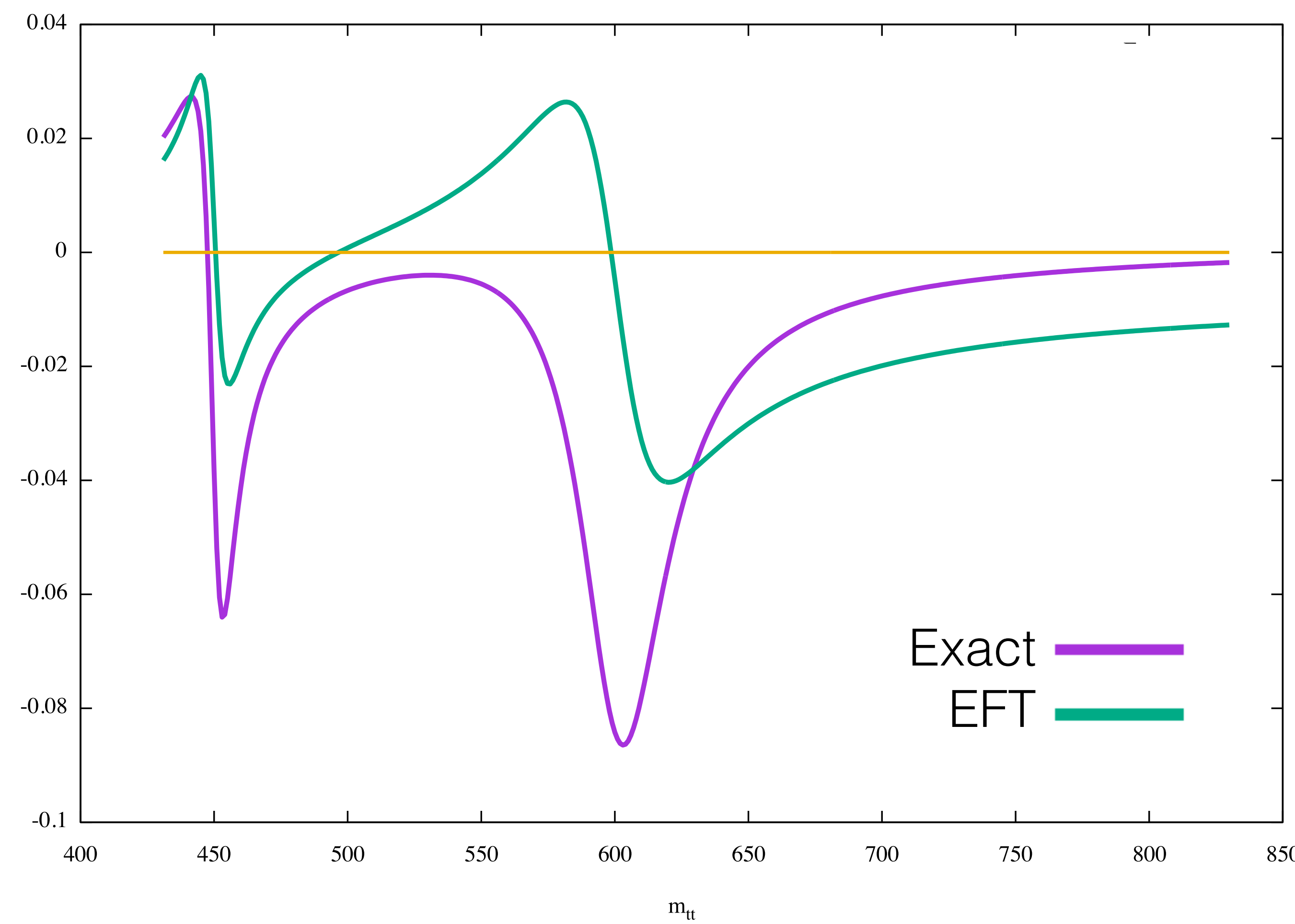


	Type	$\tan\beta$	$\sin(\beta-\alpha)$	m_H	m_A
B1	I	2.0	1.0	300	450
B2	II	0.9	1.0	450	600

One or two resonances depending on masses

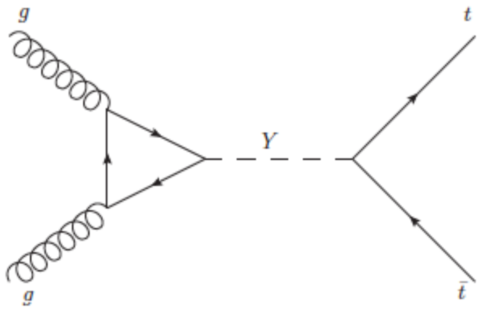
How bad is the EFT in this case?





Exact and EFT: phase difference

Top-loop induced scenarios: 2HDM



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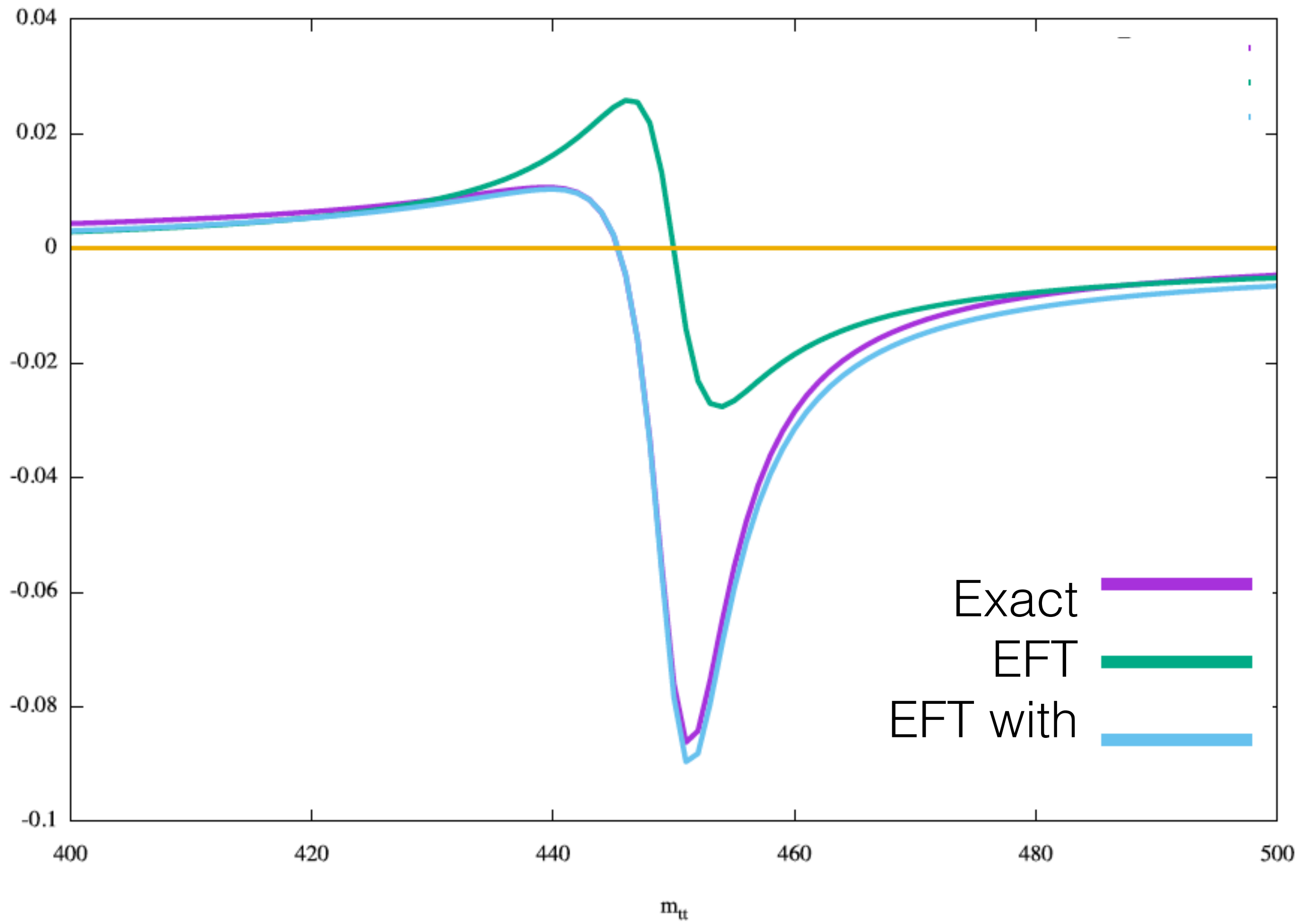
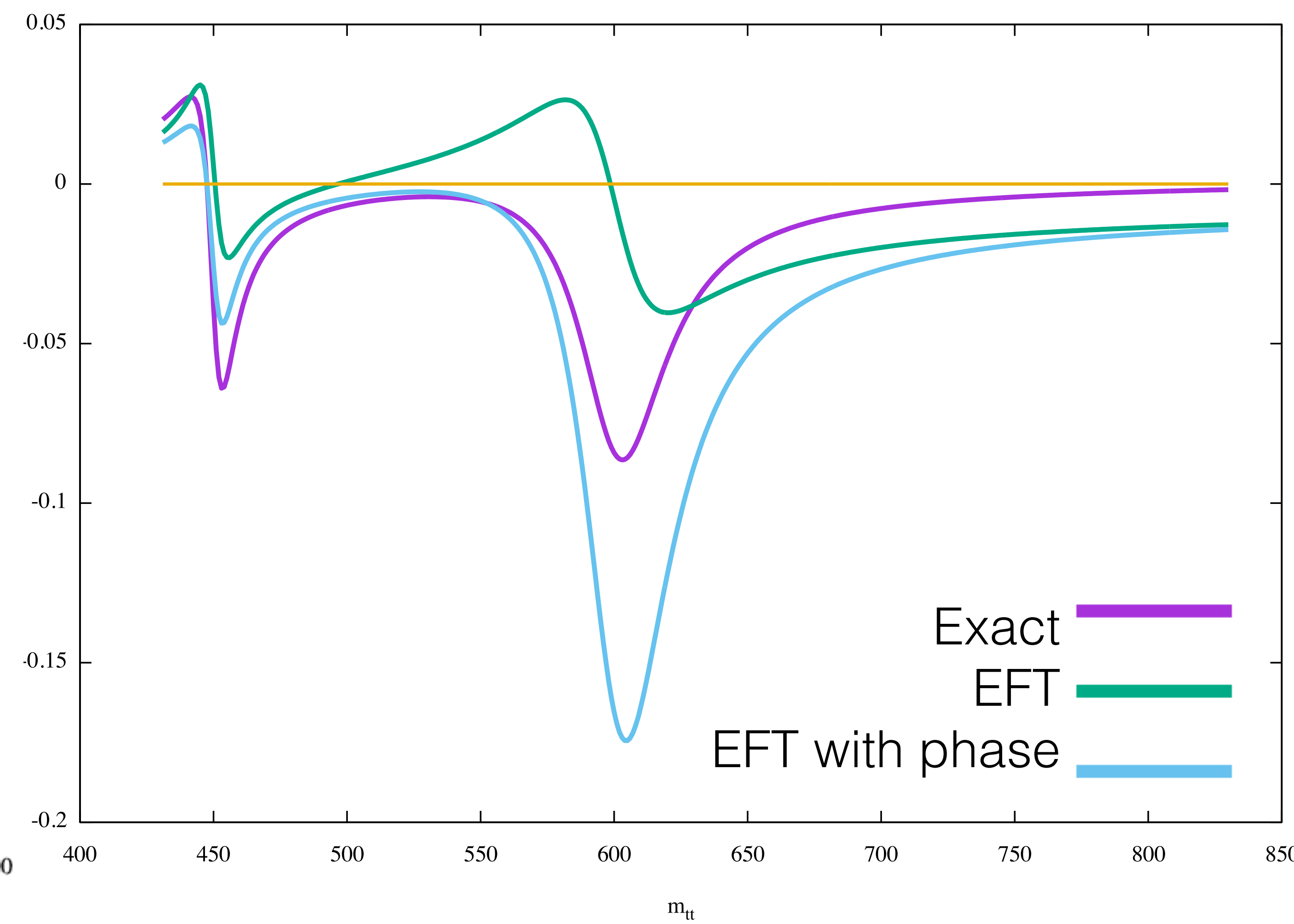


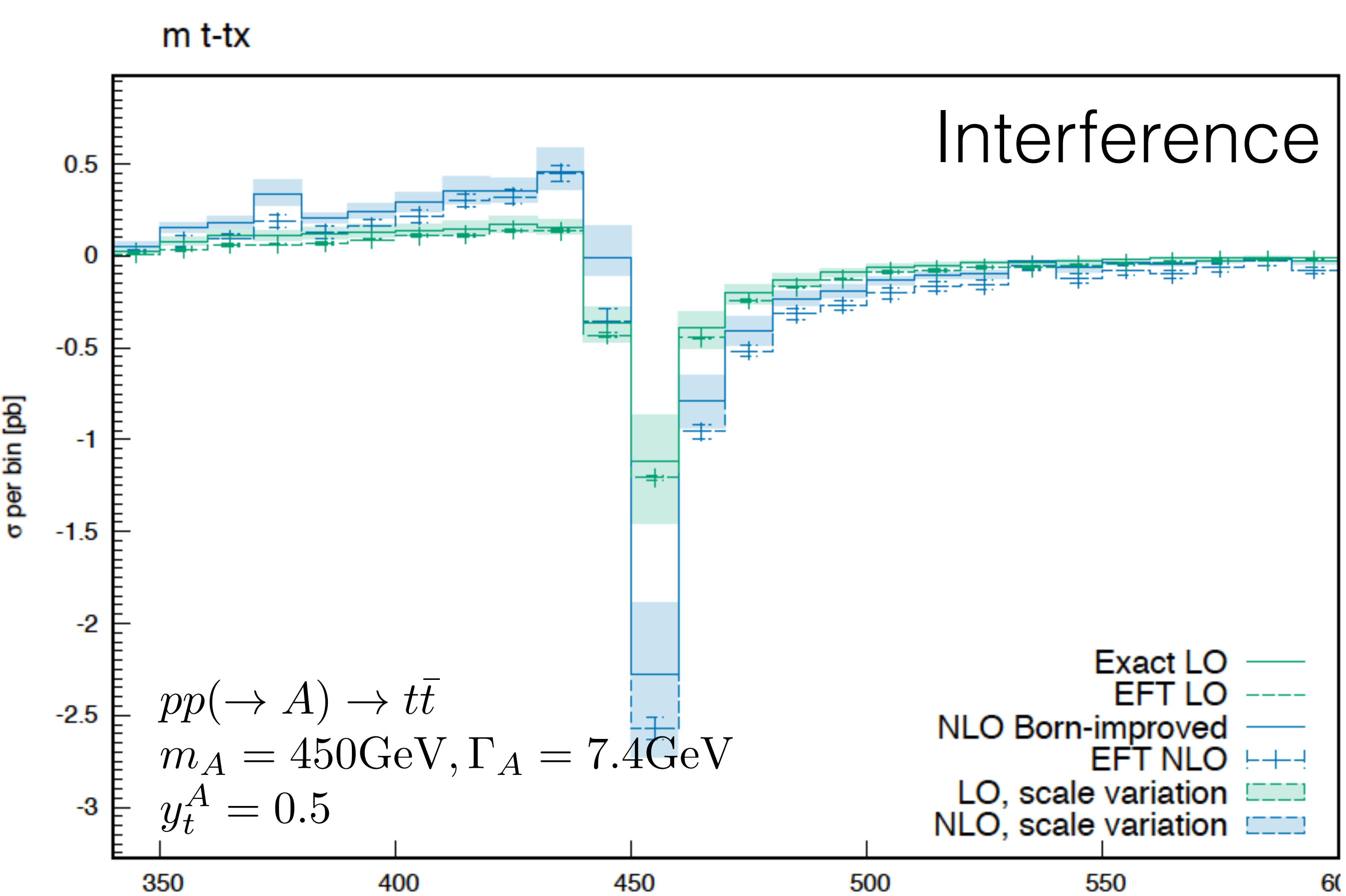


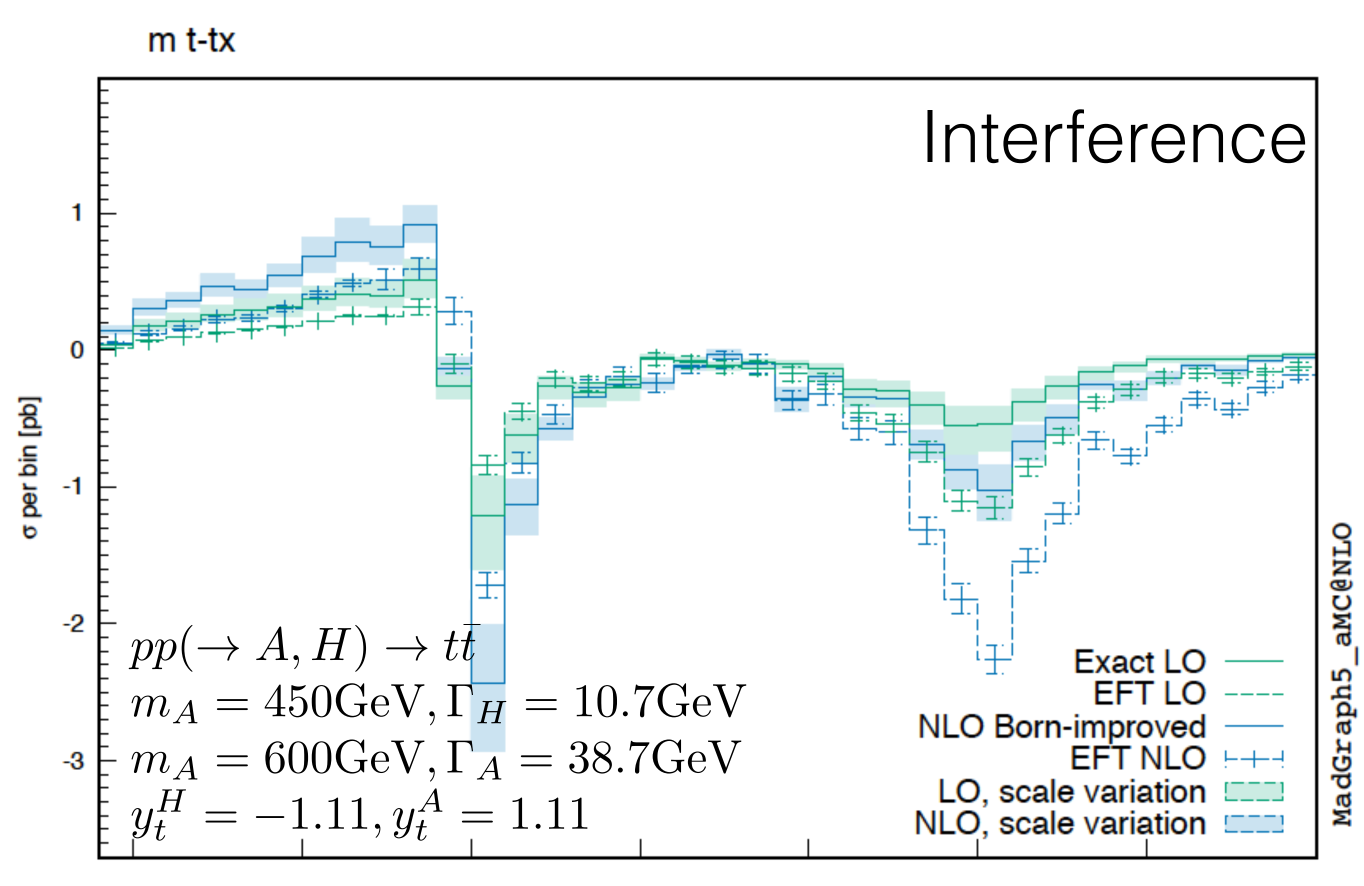
Exact and EFT: phase difference → Introducing a phase

$$c'_{HG} = c_{HG} \cdot (a + bi)$$

Results for the 2HDM

- Can we obtain results beyond LO?
- Use Born reweighting at NLO using the ratio $\mathcal{B}_{FT}/\mathcal{B}_{HEFT}$ on an event-by-event basis (known to work well for single Higgs-even heavy mass)
- Use phase-improved EFT to avoid infinities?





Preliminary

Conclusions-Outlook

- Top-anti-top resonances: an interesting possibility in various BSM scenarios
- Experimental searches demand a good theoretical description for the signal, background and interference
- Interference computed for the first time at NLO in QCD in the EFT limit (heavy quark in loop), taking into account all relevant operators
- Scenarios with dominant top-loop contributions can be possibly improved by reweighting
- Subtleties related to treatment of resonances in the parton shower to be further investigated