Interference effects in resonance production and decay into top pairs

Eleni Vryonidou
Nikhef
based on arXiv:1606.04149 with B. Hespel and F. Maltoni and
work progress with D. Franzosi and C. Zhang

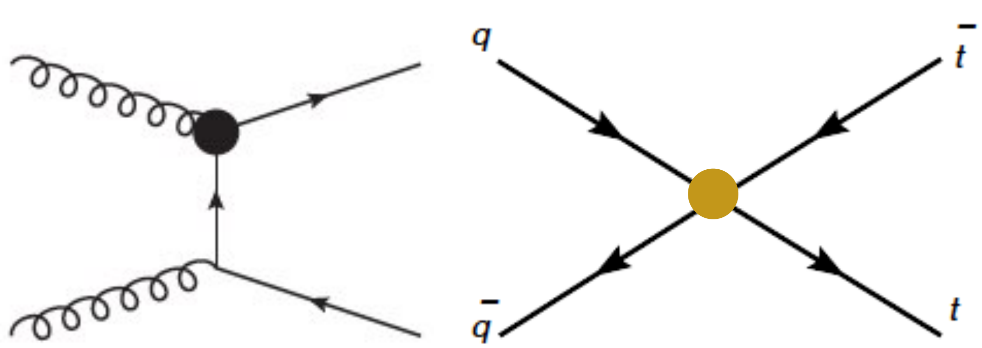
LHCP2017,
Shanghai 19/5/17

New physics in top pair production

No new light states

SMEFT: Dimension-6 operators

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



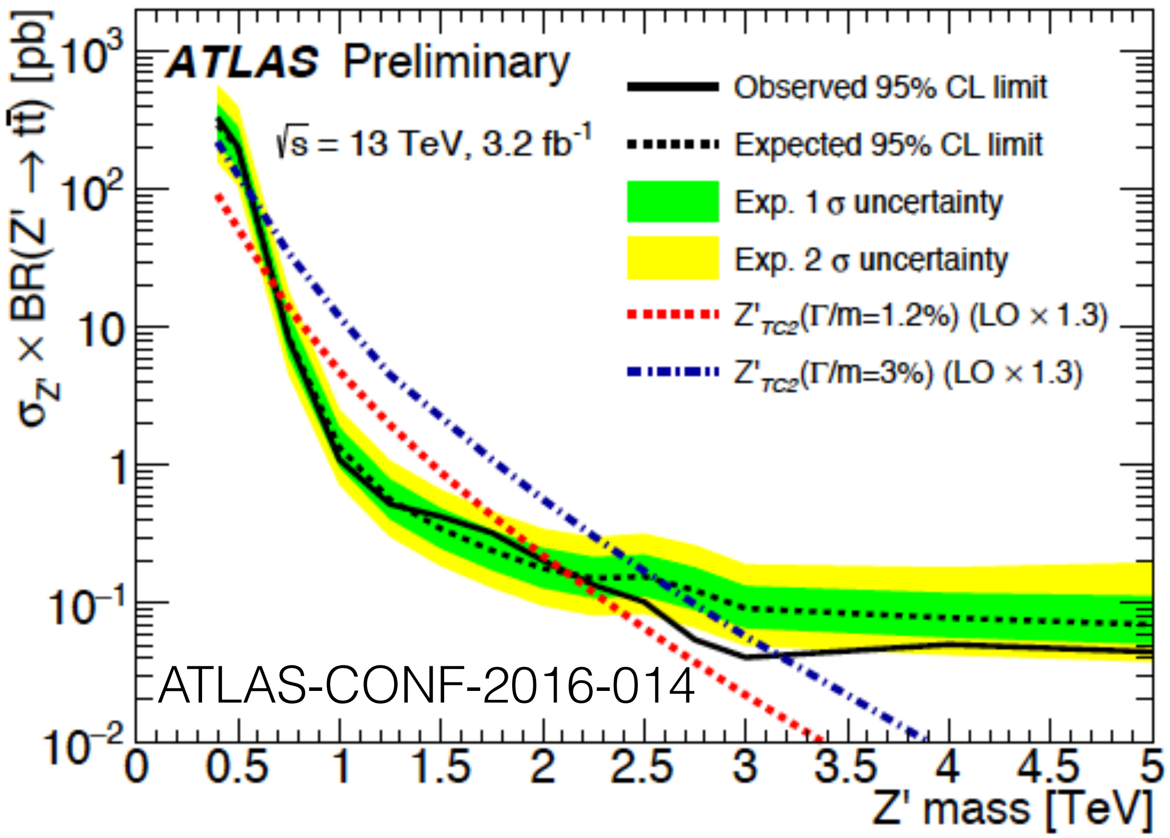
Typically deviations in the m_{tt} tails, see top plenary talk C. Zhang

New particles: Top resonances

A wide range of possibilities

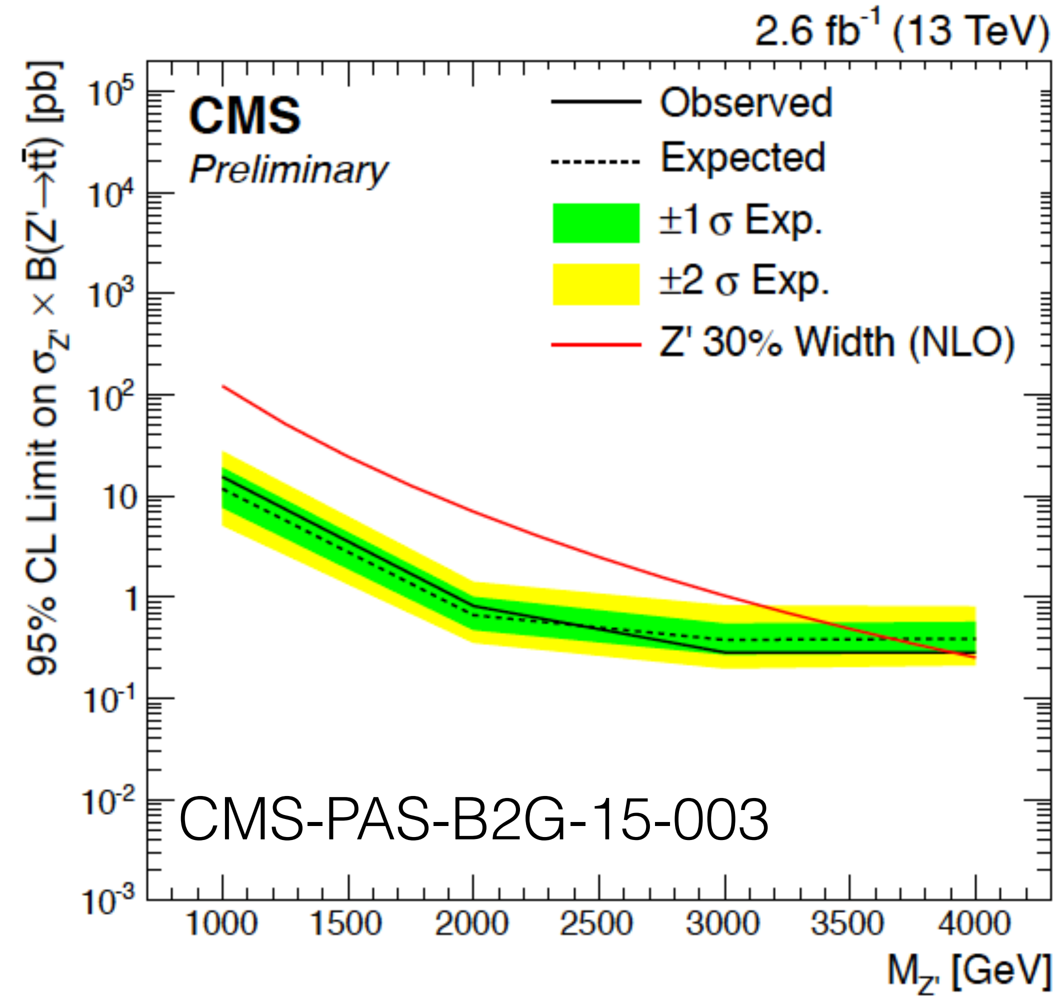
- Spin 0 colour singlet
  - SUSY, 2HDM
- Spin 0 colour octet
  - MFV models
- Spin 1 colour singlet
  - Z'
- Spin 1 colour octet
  - KK gluons, colorons, axigluons
- Spin 2 colour singlet
  - Gravitons

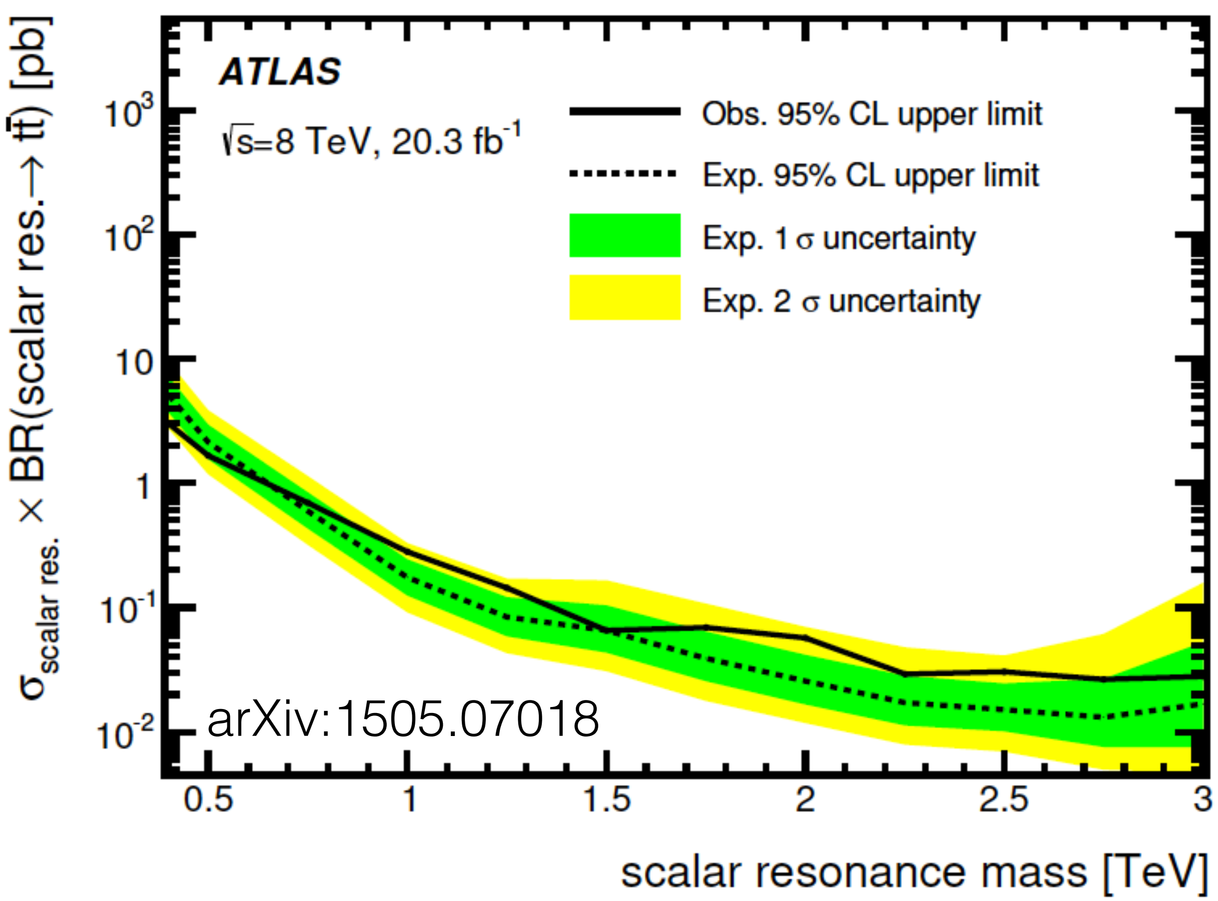
LHC searches for resonances



ATLAS and CMS searches (see talk in this session):

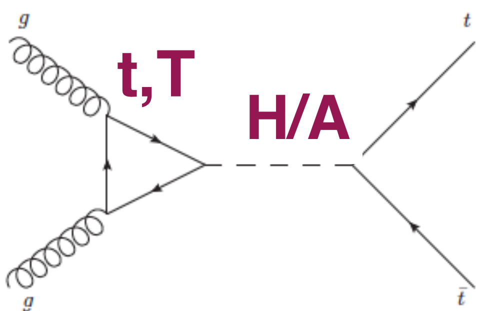
- Resolved (low mass)
- Boosted (high mass)



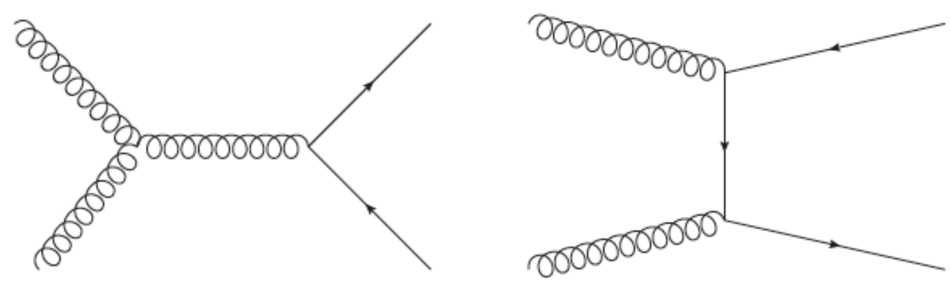


+KK-gluon and 2HDM interpretations
ATLAS-CONF-2016-073

Scalar resonances in $t\bar{t}$



signal

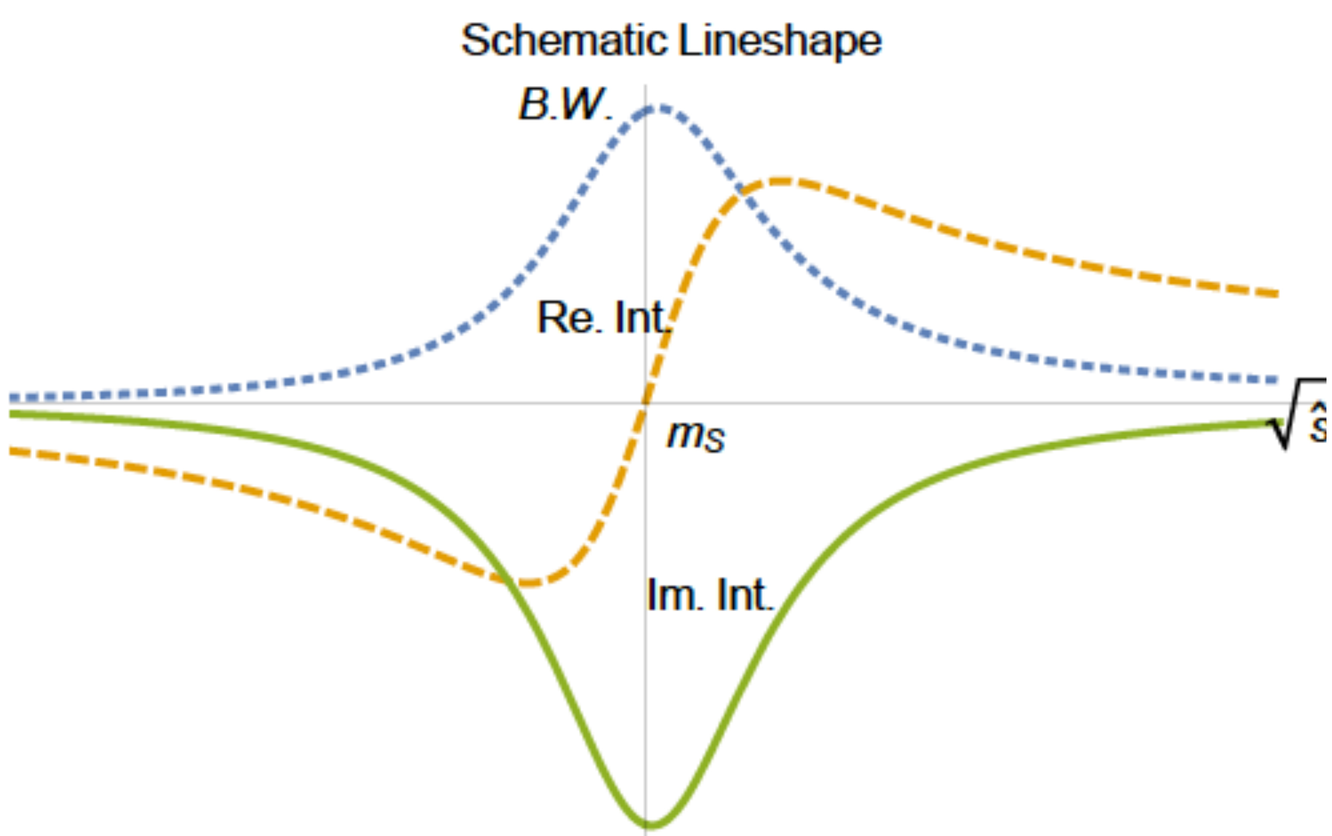


QCD continuum

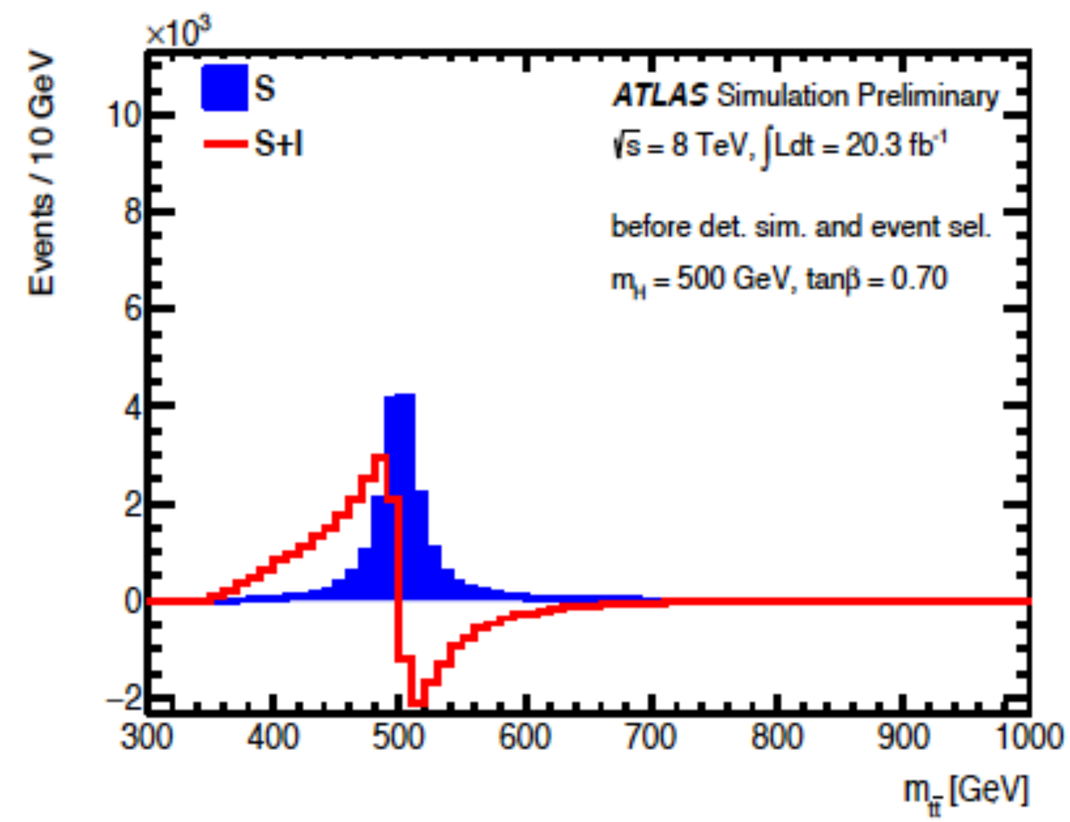
Interference important for the line shape for widths~0.01M

Peak-dip structures

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

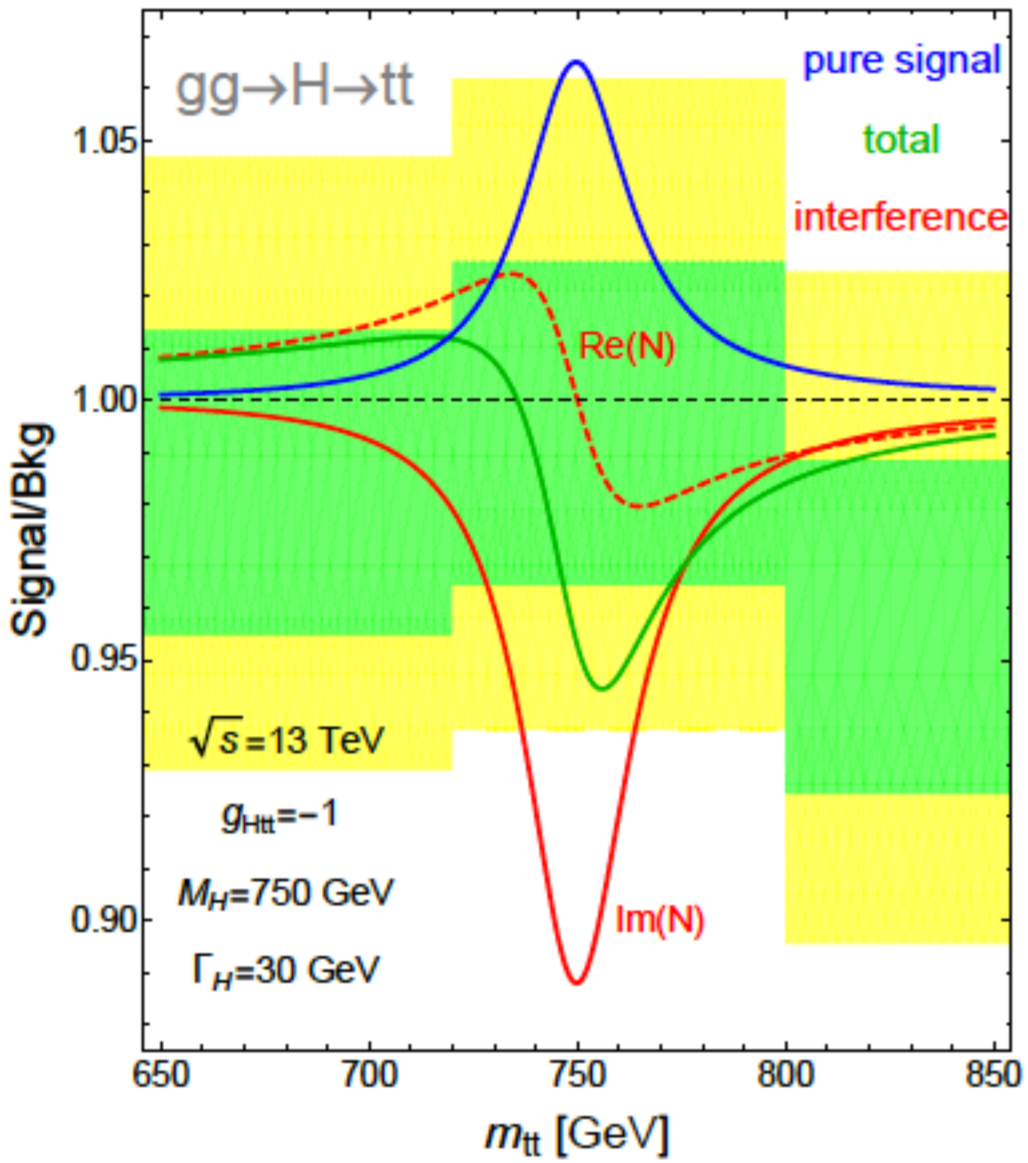


Carena, Liu arXiv: 1608.07282

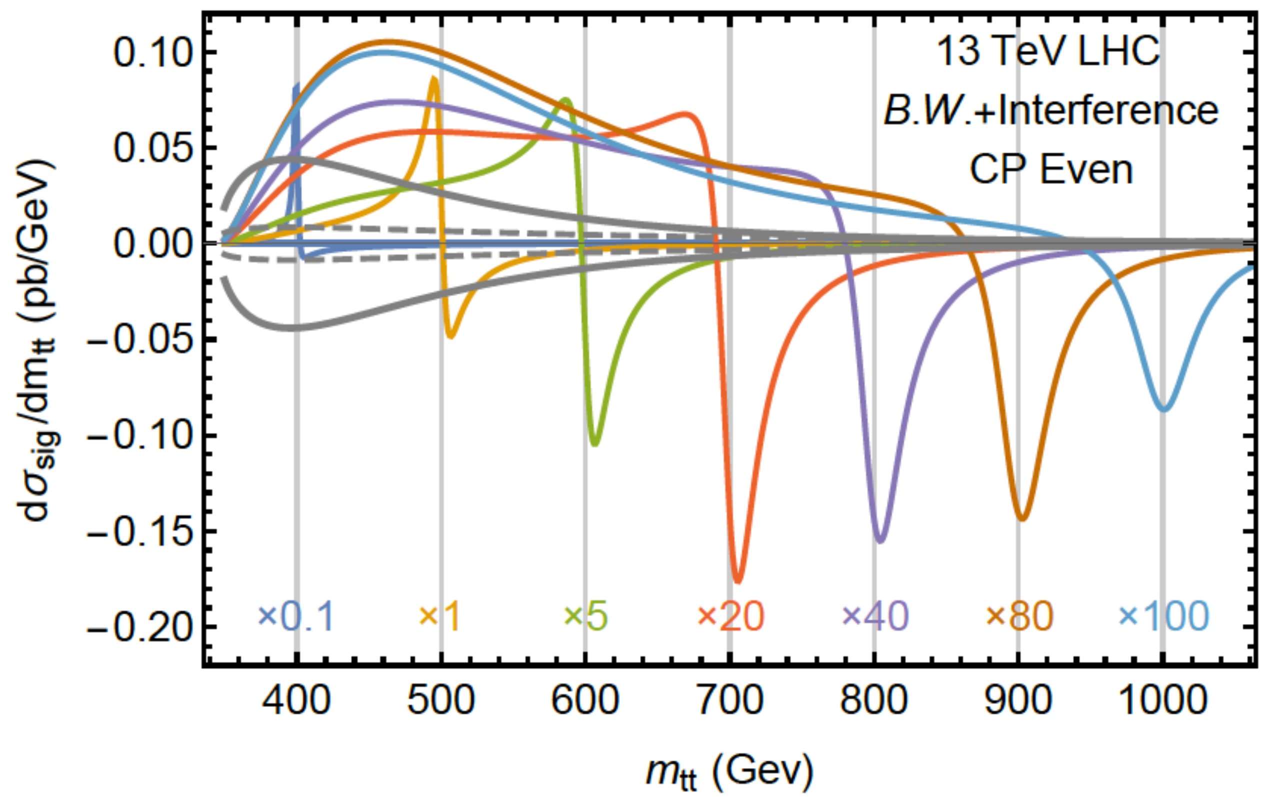


ATLAS-CONF-2016-073
First experimental study modelling the interference

Line-shapes



Ellis, Djouadi, Quevillon arXiv:1605.00542



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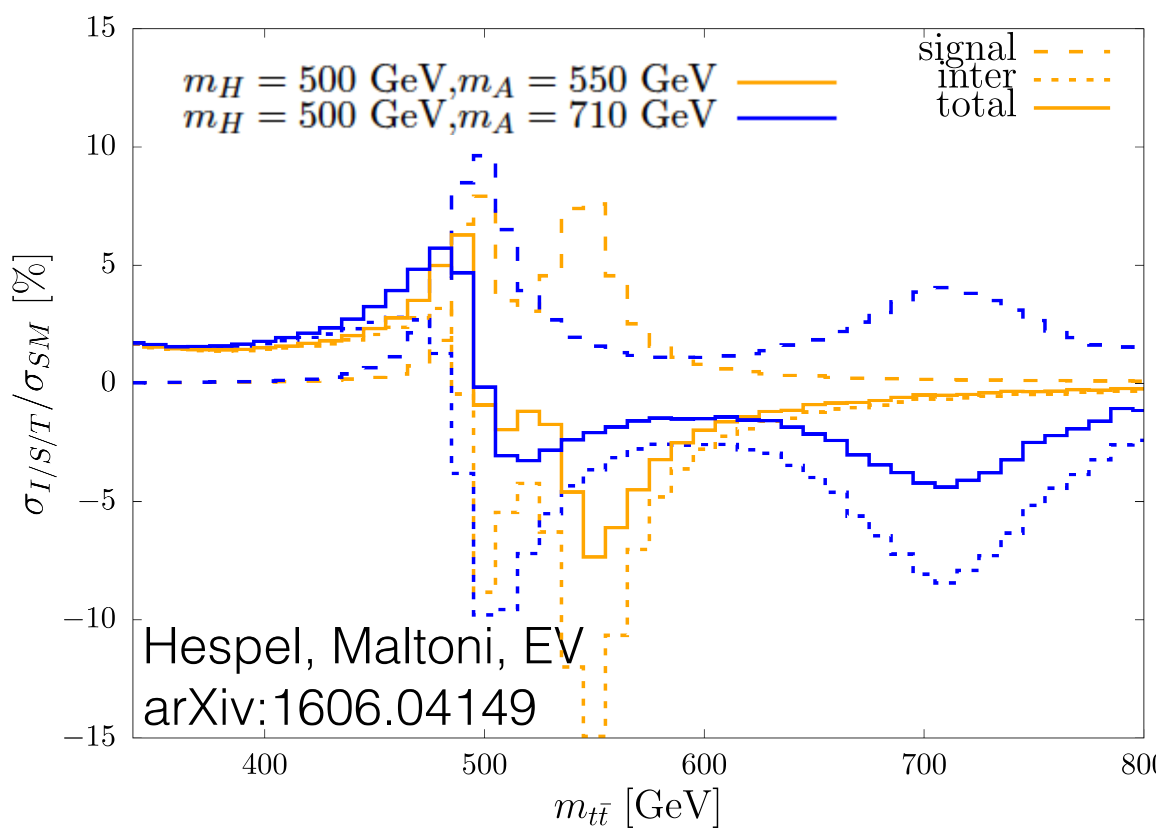


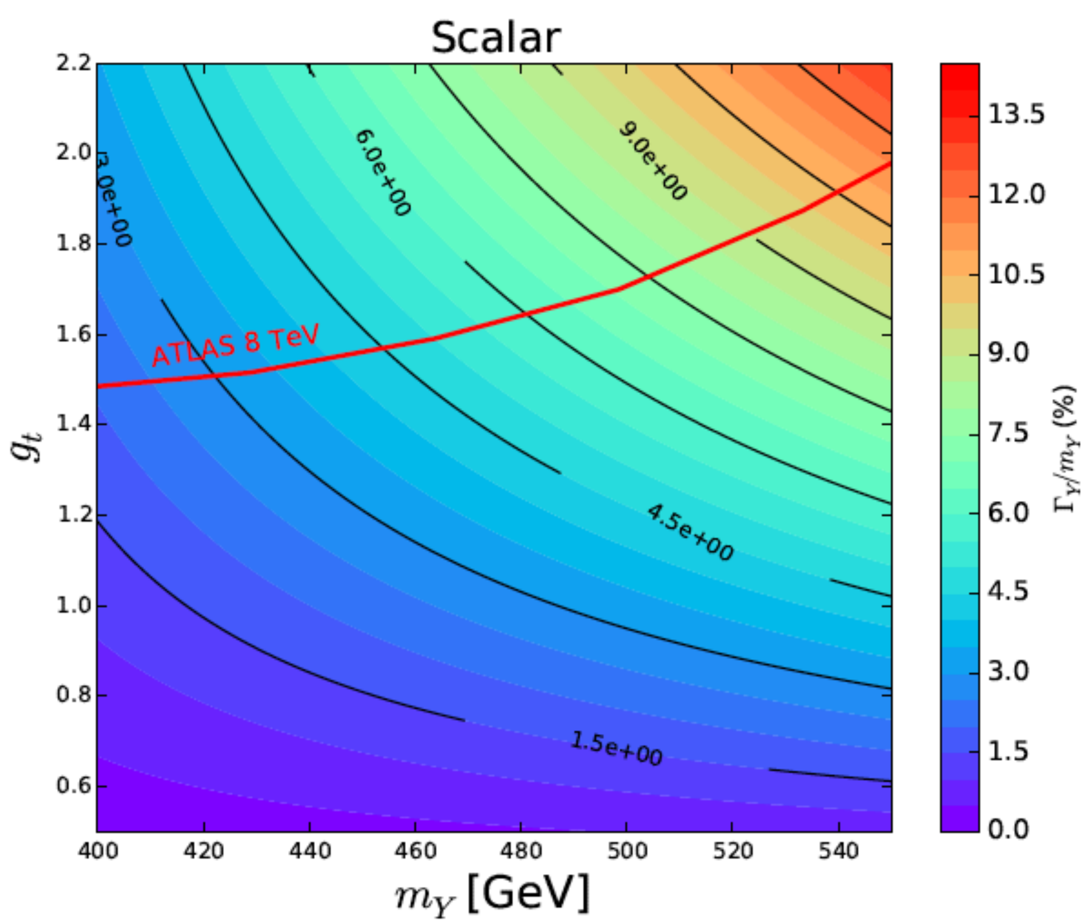
Hespel, Maltoni, EV
arXiv:1606.04149

Lineshape largely different from BW in realistic BSM scenarios

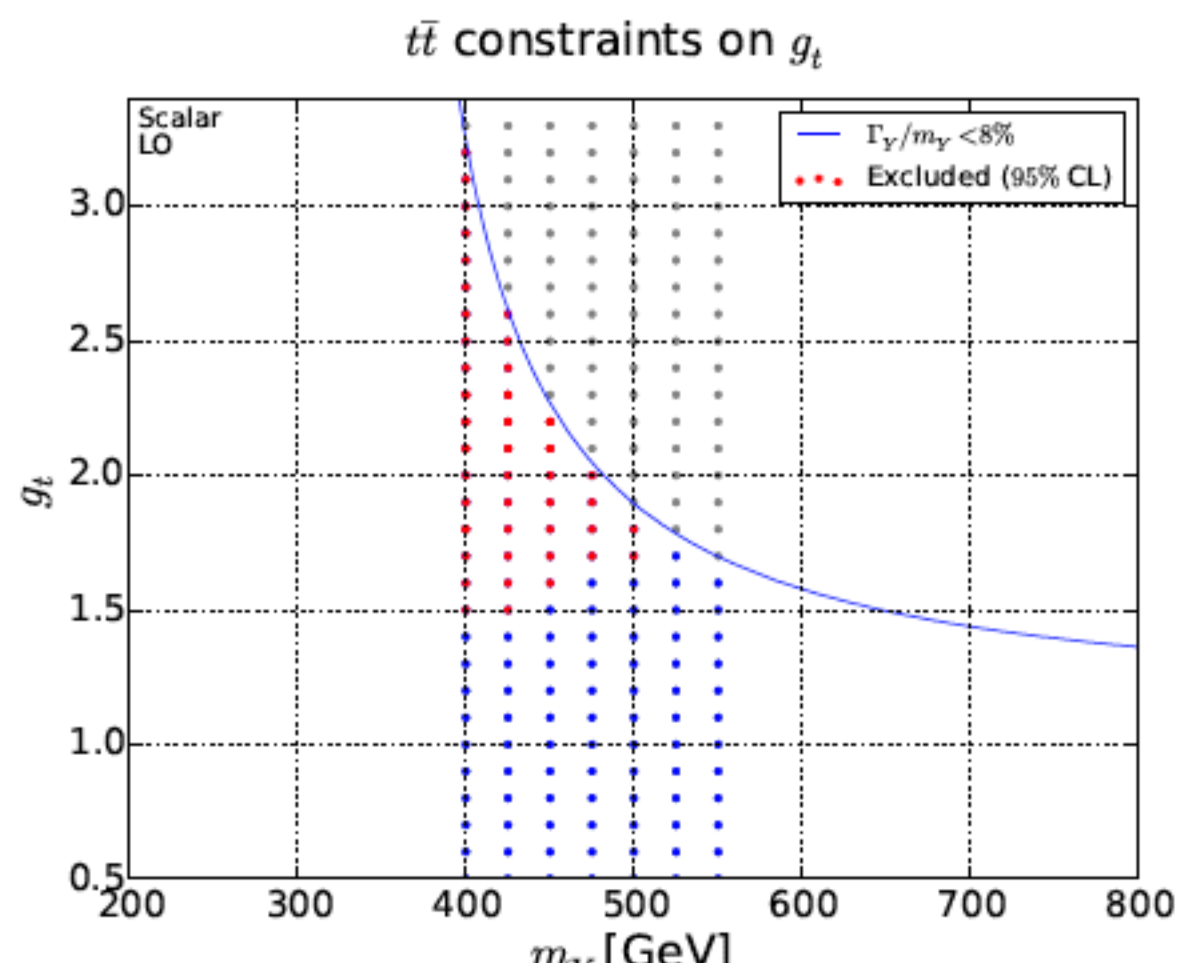
Impact of interference on limits for a simplified model

ATLAS 8TeV resonance search: arXiv:1505.07018
Narrow width ~3%, limits on σ x Br as a function of M

Simplified model $\mathcal{L} = \bar{t}\frac{y^t}{\sqrt{2}}(g_t^S + i g_t^P \gamma^5) t Y$



Hespel, Maltoni, EV arXiv:1606.04149



Exclusion region affected by taking into account the interference

Impact of interference on limits for a simplified model

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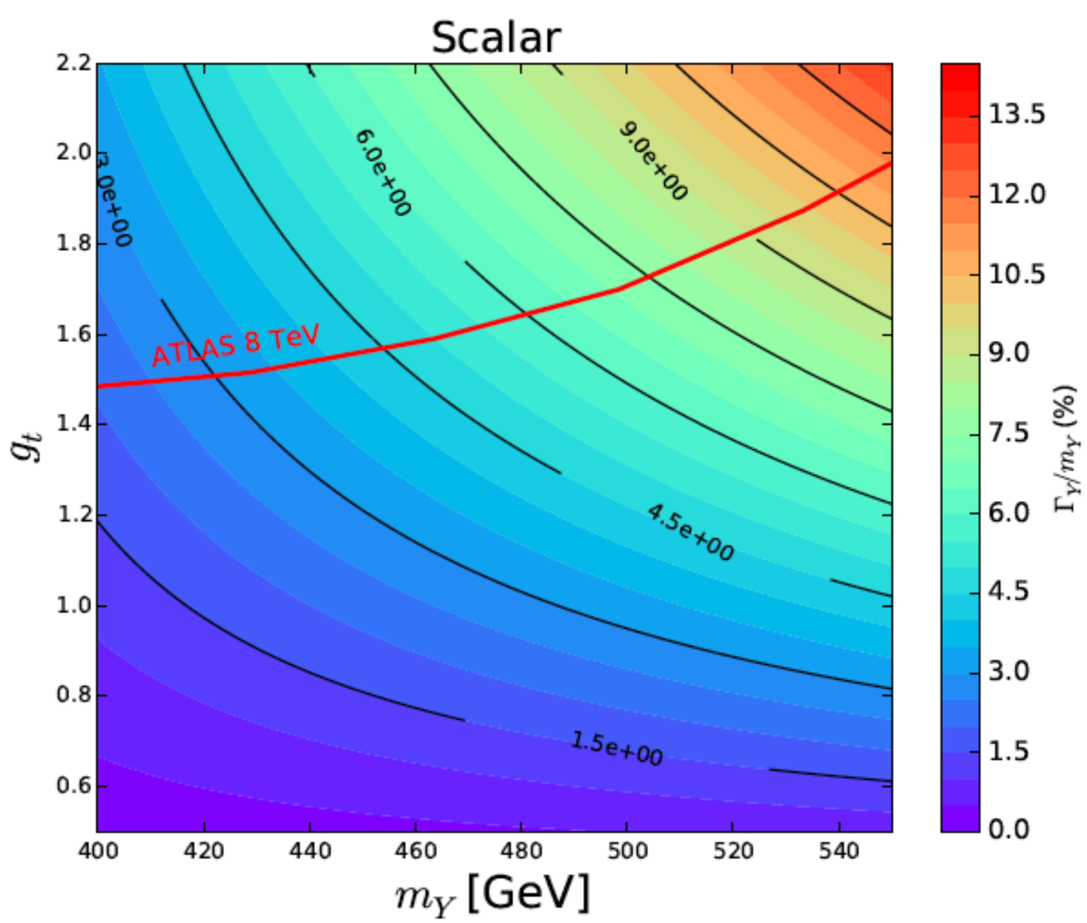
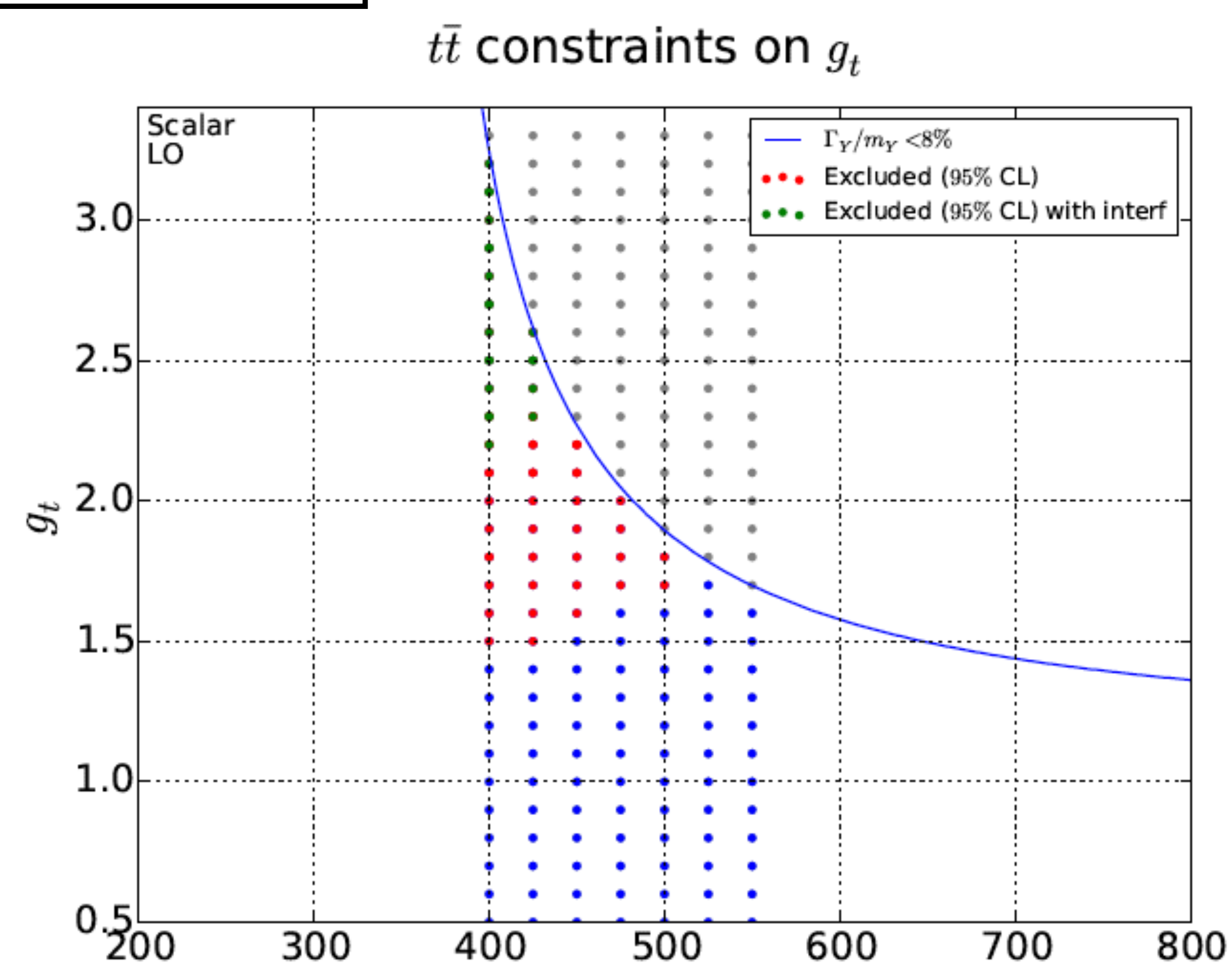




Hespel, Maltoni, EV arXiv:1606.04149

Exclusion region affected by taking into account the interference

Theory predictions for the line shapes

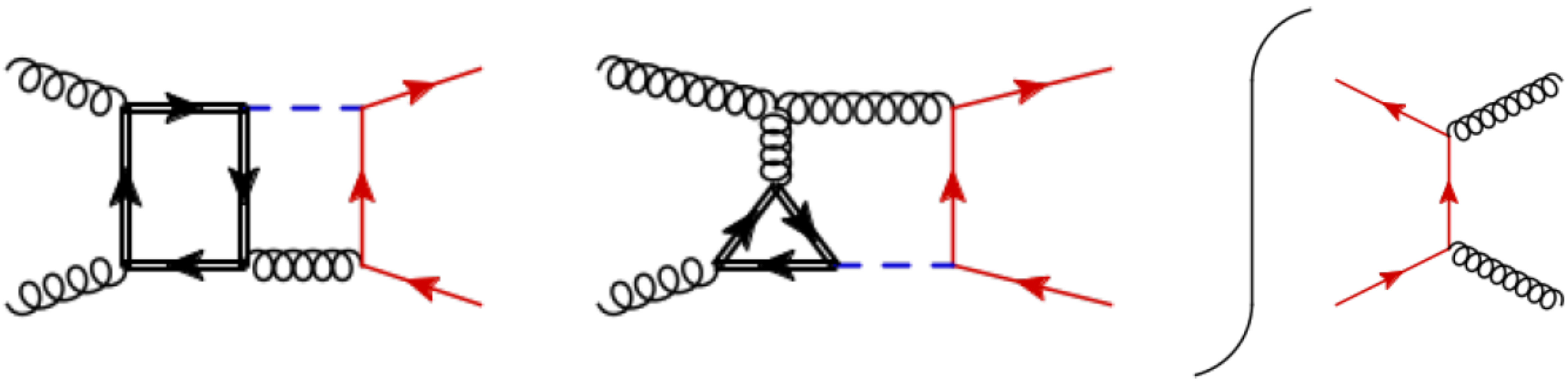
- Interference: crucial for a realistic description of the line shape (in particular for a gluon initiated scalar resonance) and for interpreting experimental exclusion limits for BSM models

- Experiments moving towards including this interference: optimised experimental strategies beyond Breit-Wigner ATLAS-CONF-2016-073 for top pair production

- Need for precise predictions:
  - Background: NNLO QCD Czakon, Mitov et al arXiv:1601.05375, 1606.03350, NNLO QCD+ NLO EW Czakon et al arXiv:1705.04105
  - Signal: NLO (higgs production and decay into heavy quarks)
  - Interference: formally 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

Signal and background known at NLO

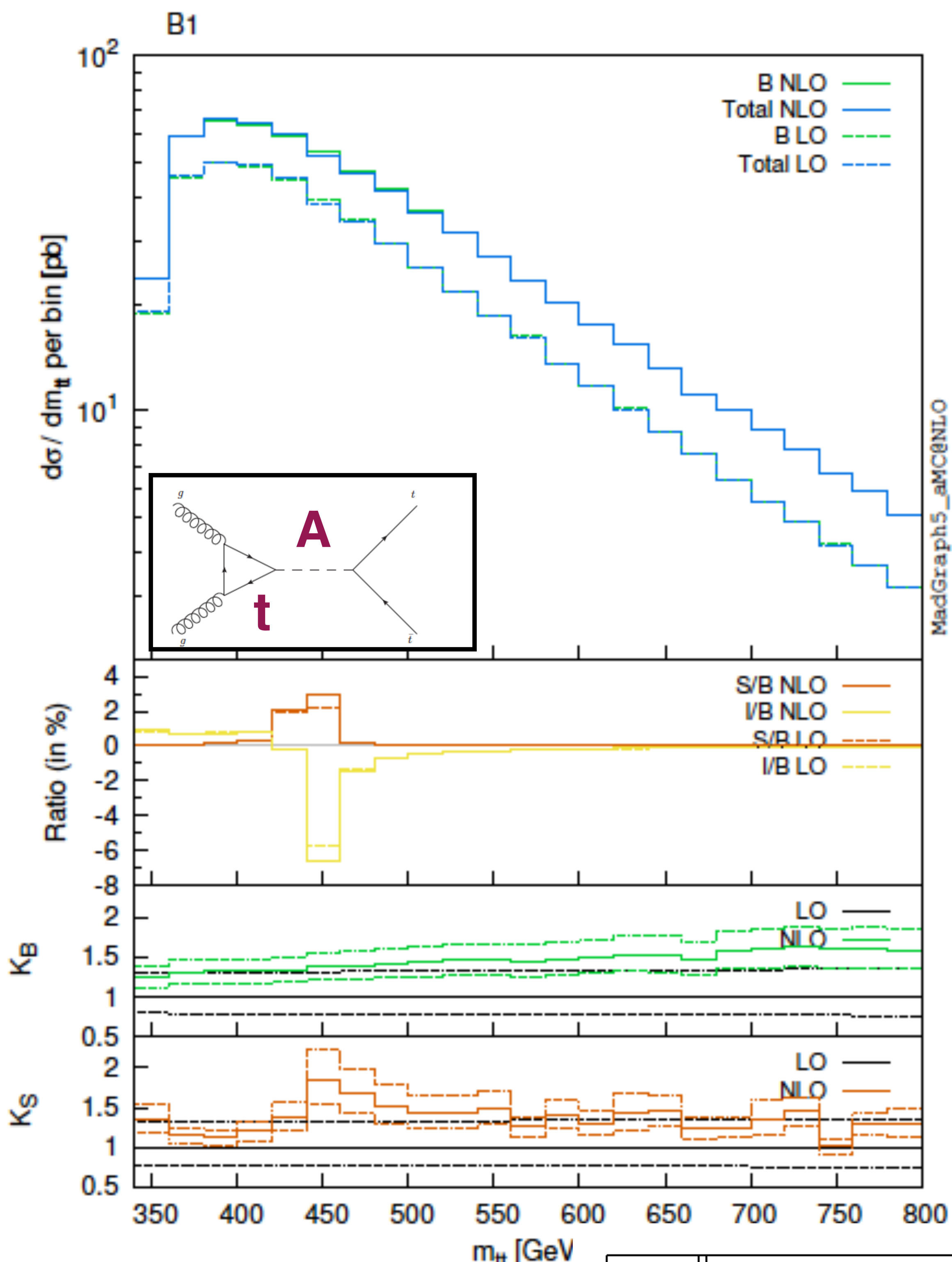
Use of K-factor approximation in

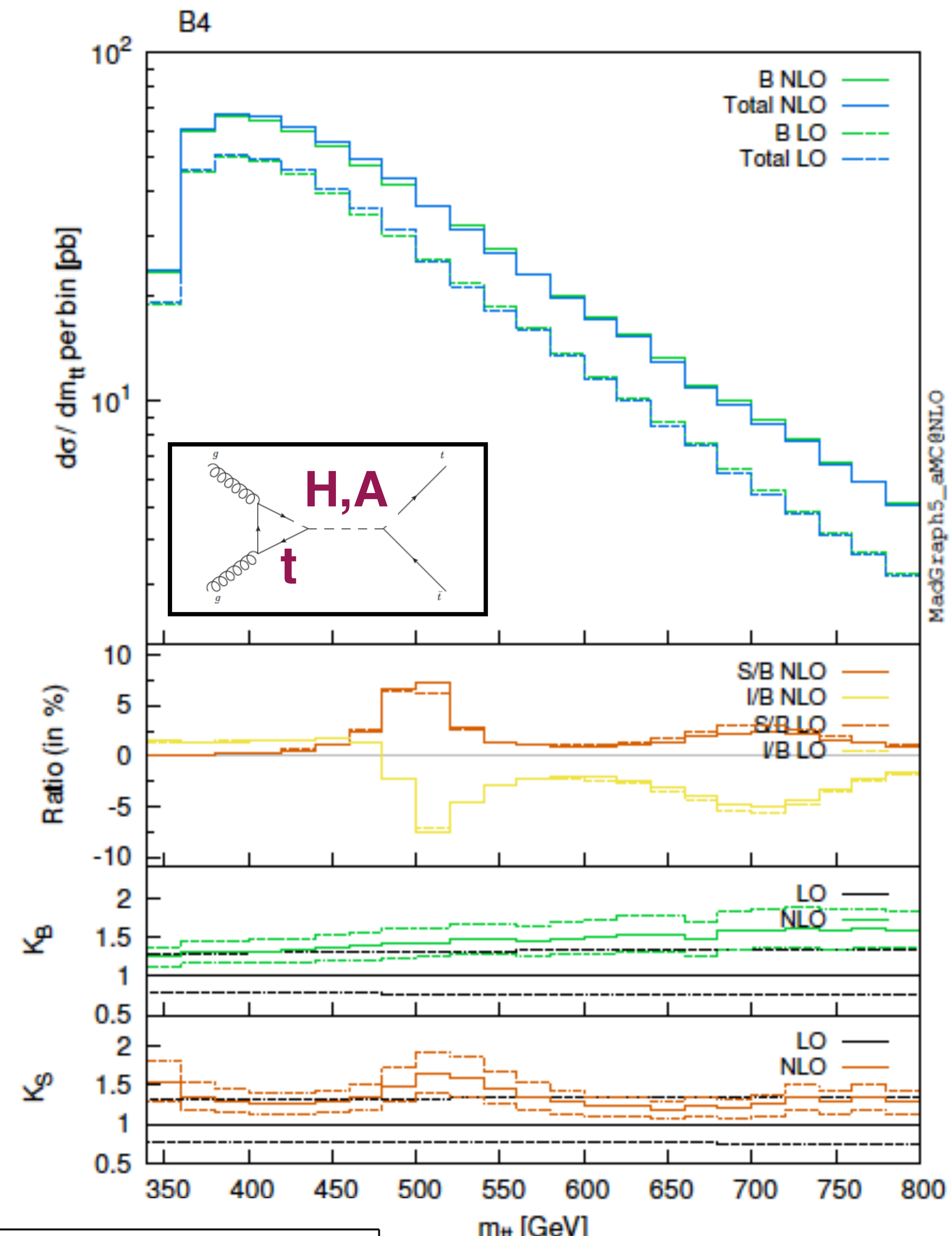
Hespel, Maltoni, EV arXiv:1606.04149

$$\sigma_{\mathrm{NLO}} = \sigma^{\mathrm{back}}_{\mathrm{NLO}} + \sigma^{\mathrm{signal}}_{\mathrm{NLO}} + \sigma^{\mathrm{inter}}_{\mathrm{LO}} \sqrt{K_S K_B}$$

(bin-by-bin)

2HDM Results



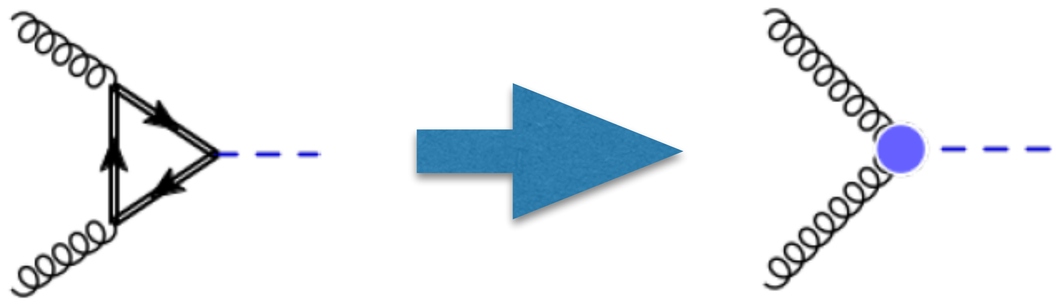


	$\tan\beta$	α/π	m_{H^0}	m_{A^0}	$m_{H^\pm}$	m_{12}^2
B1	1.75	-0.1872	300	441	442	38300
B4	0.6	-0.328	500	710	720	10000

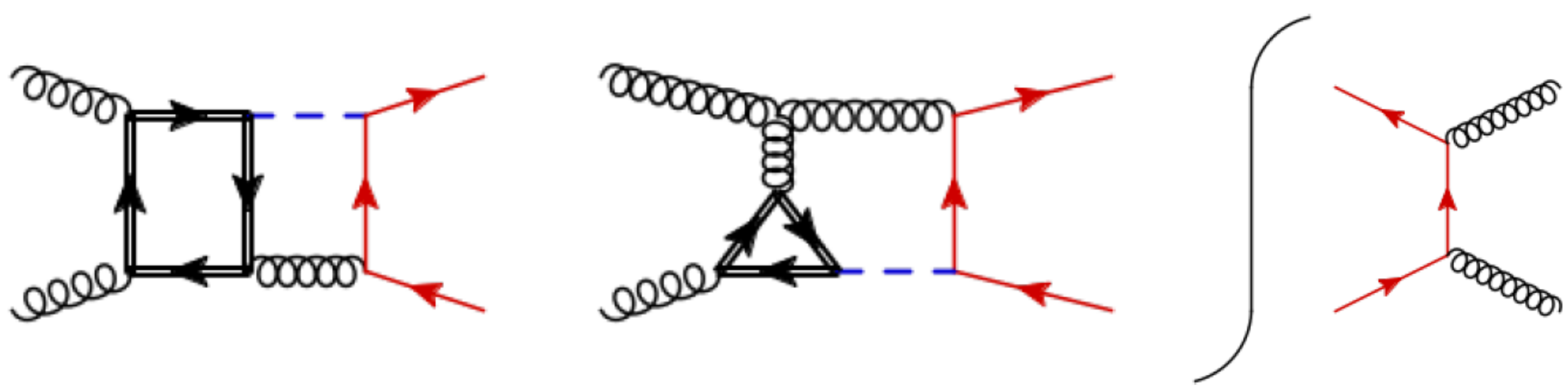
See also: Bernreuther et al. arXiv:1511.0558

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

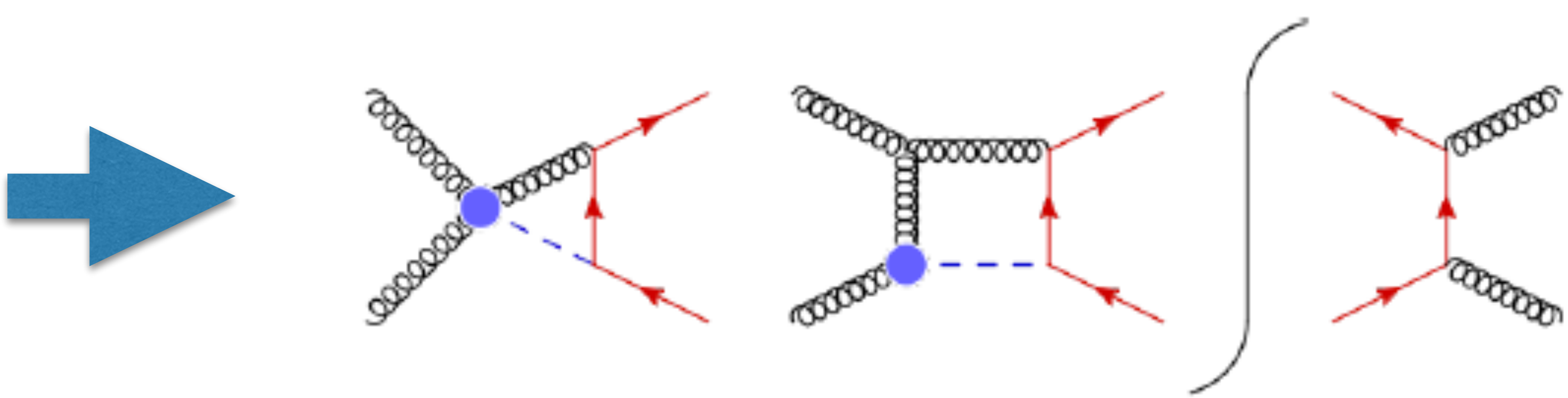
What if a heavy quark runs in the loop?
The EFT limit



LO

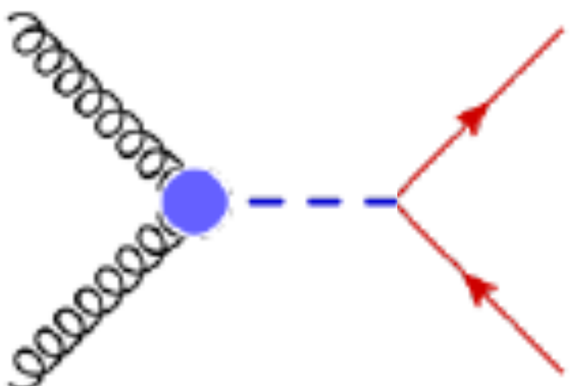


NLO

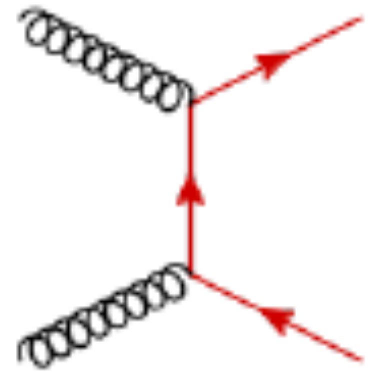


2-loop
becomes
1-loop

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



Signal



Background

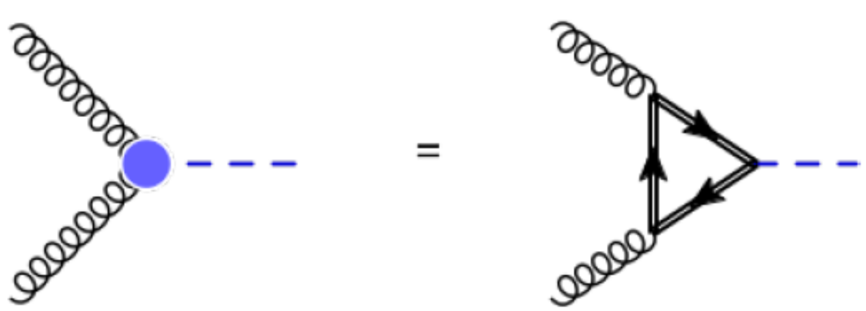
Exact for heavy VLQ running in the loop

$$O_{HG} = g_s^2 G^A_{\mu\nu} G^{A\mu\nu} H$$

and/or

$$O_{A\tilde{G}} = g_s^2 G^A_{\mu\nu} \tilde{G}^{A\mu\nu} A$$

Operator coefficient can be matched to UV theory



For a VLQ coupling to a scalar

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

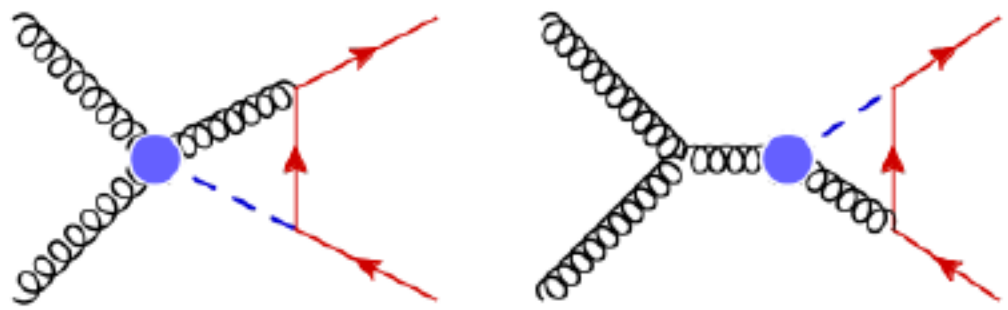
$$\frac{C_{HG}(m_F)}{\Lambda} = -\frac{y_F}{48\pi^2 m_F}$$

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

$gg \to H(A) \to t\bar{t}$ 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 $$O_{tG} = g_s y_t \bar{t} \sigma^{\mu\nu} T^A t G^A_{\mu\nu}$$

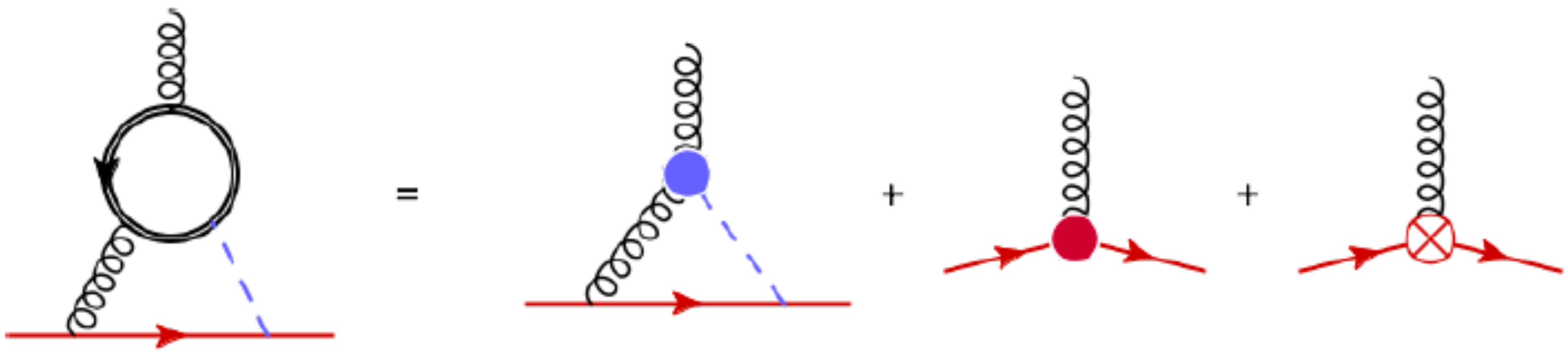
→ Needs to be added to the theory

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

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

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

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

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

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

Matching (two-loop ggH and Barr-Zee)

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

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

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

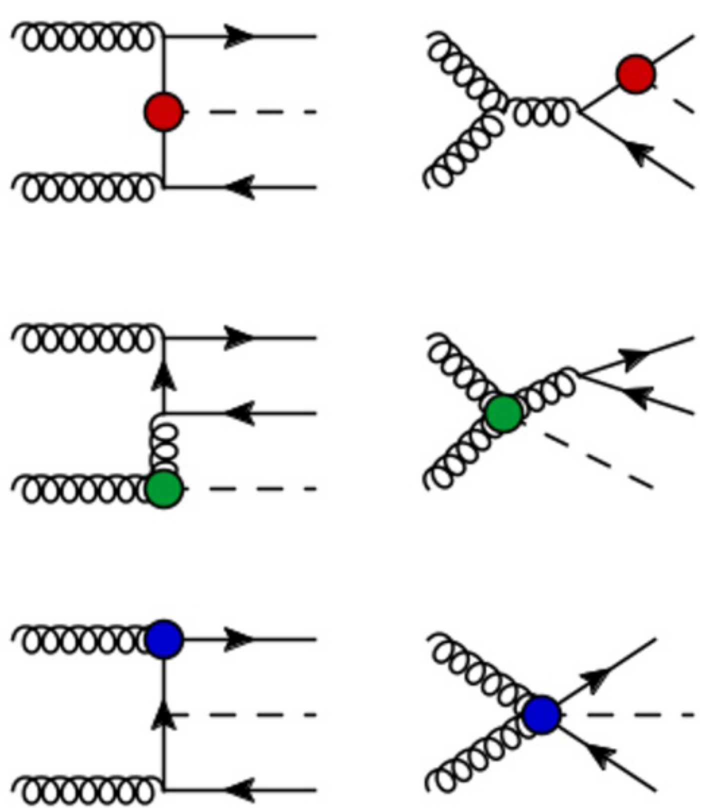
Running: RG equations

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

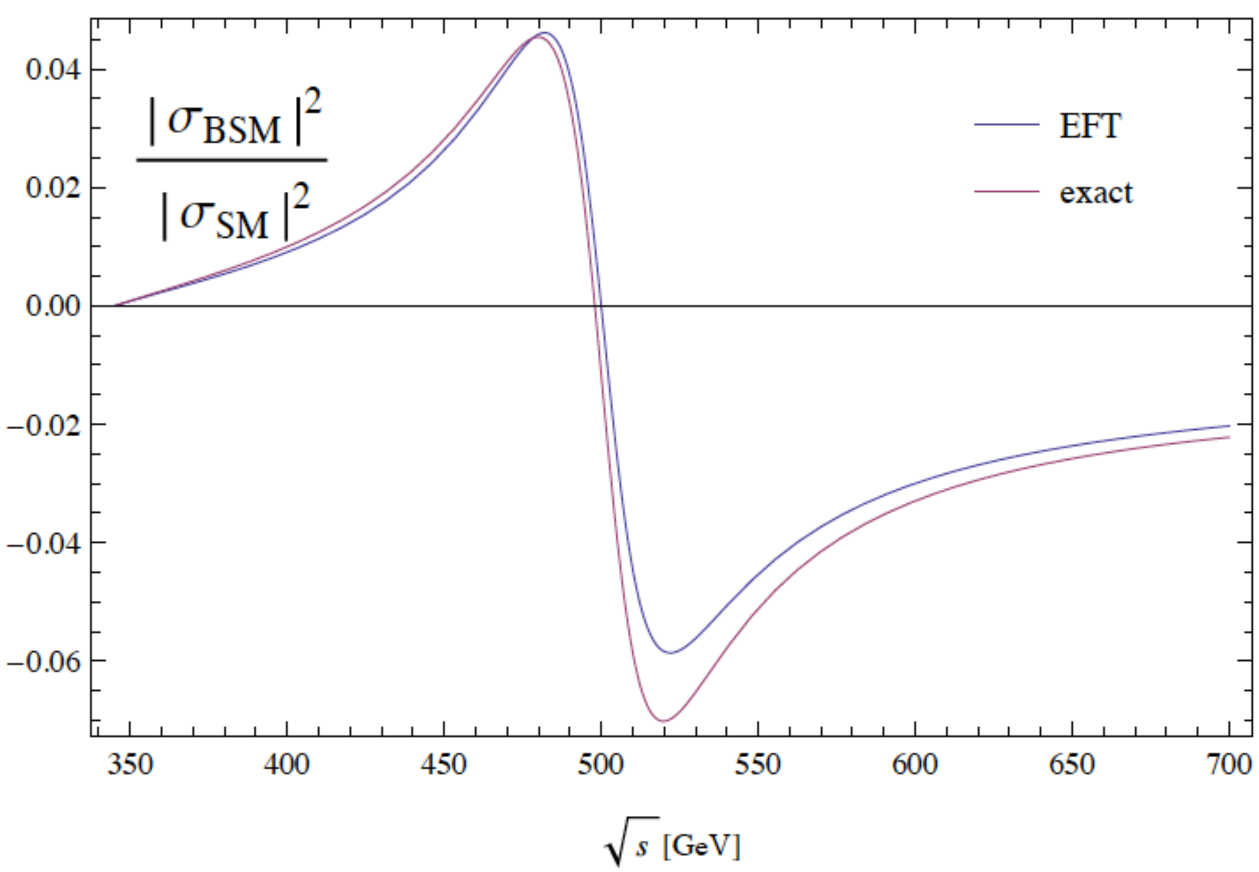
Results: VLQ loop

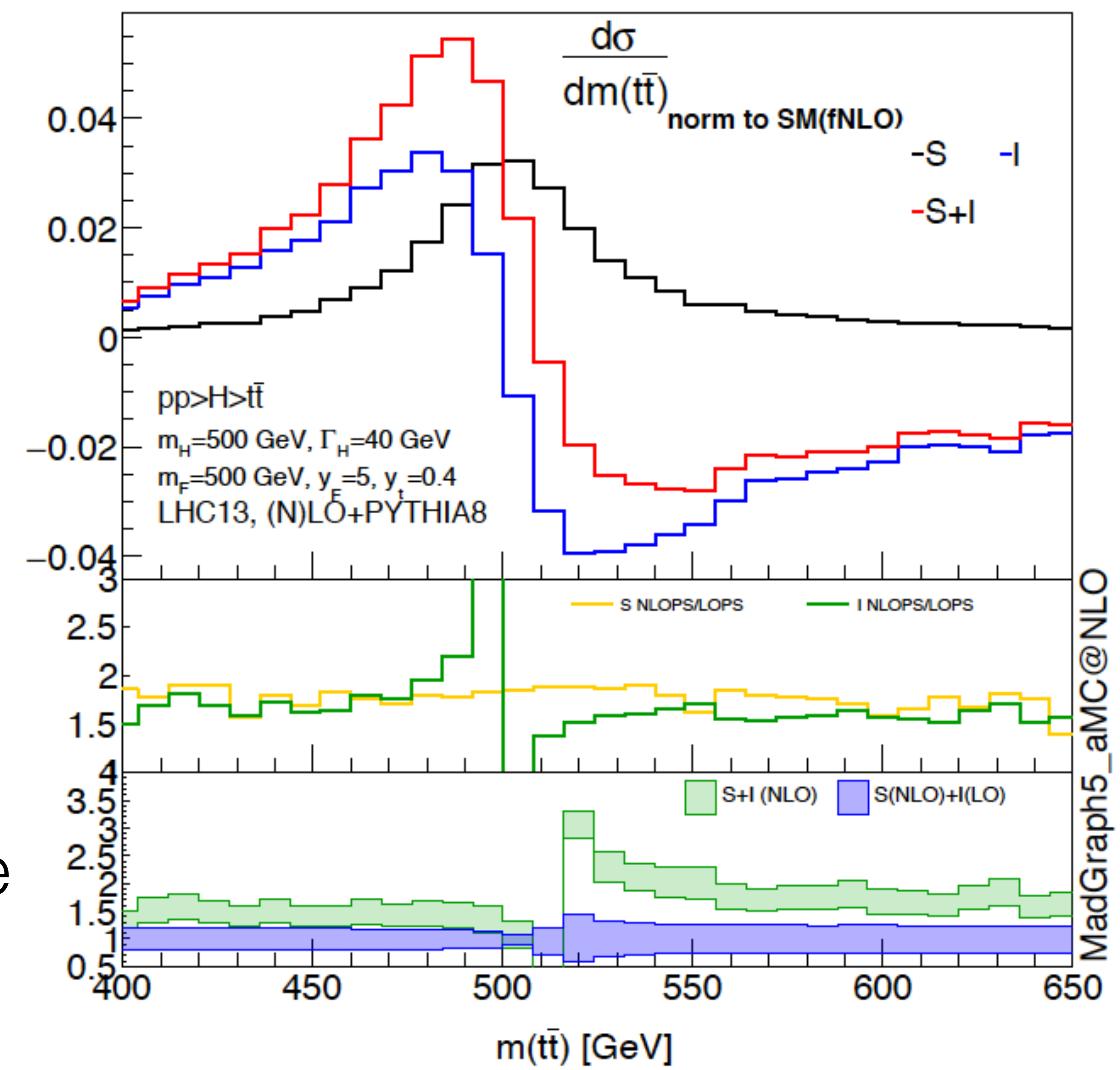
Scenario A: Heavy VLQ

m_H=500 GeV, Γ_H=40 GeV

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

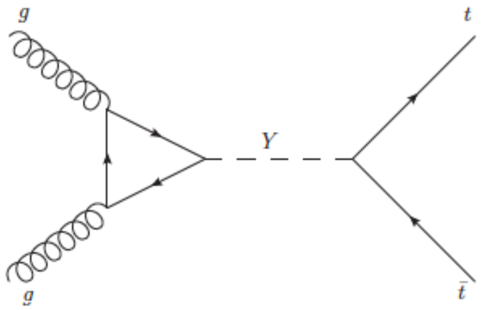
$$\frac{C_{HG}}{\Lambda} = -5.11 \times 10^{-5}\ \mathrm{GeV}^{-1}\,,$$
$$\frac{C_{tG}}{\Lambda} = -1.40 \times 10^{-6}\ \mathrm{GeV}^{-1}\,.$$





EFT: a good approximation in this case
Dominated by VLQ loop

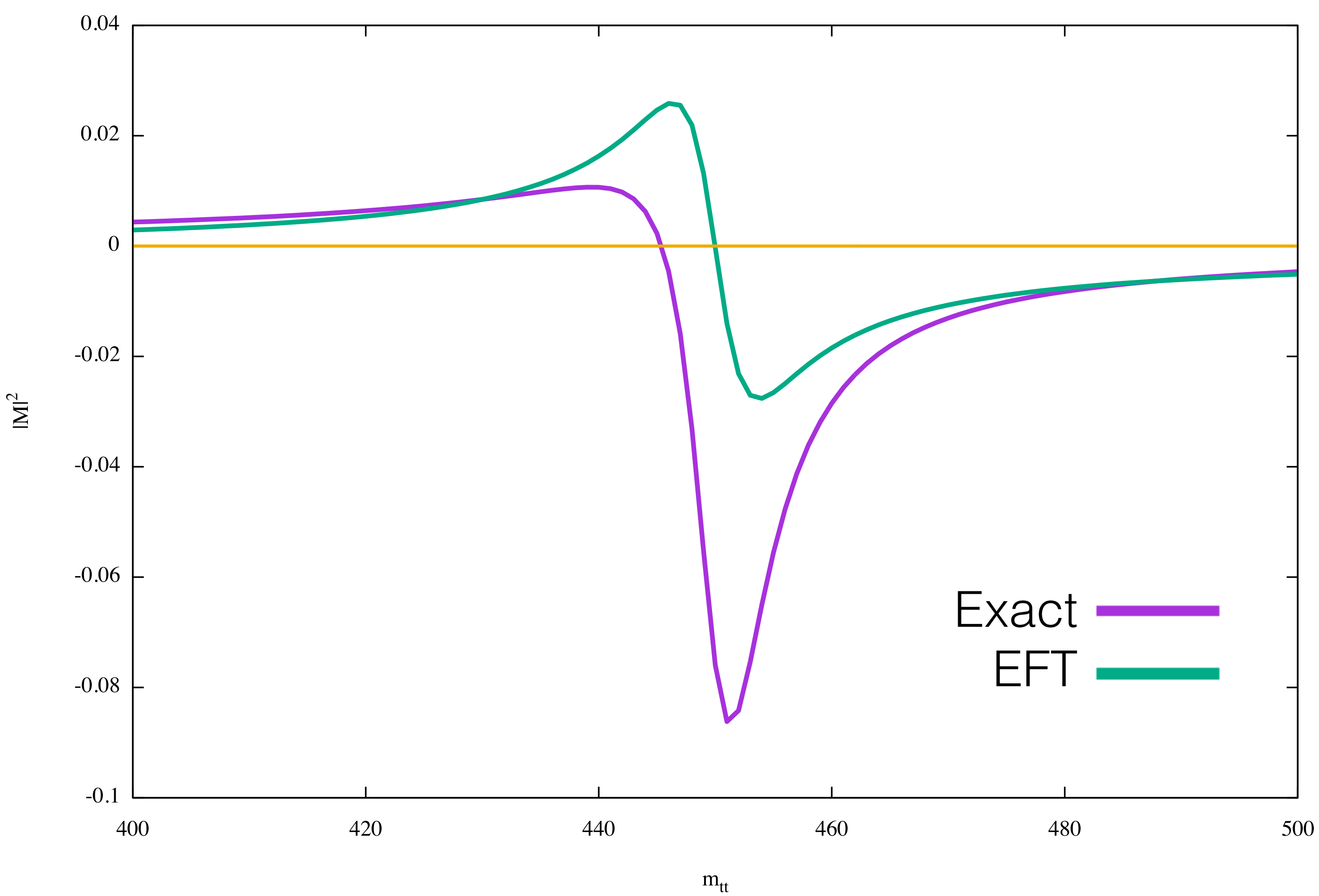
Top-loop induced scenarios: 2HDM



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

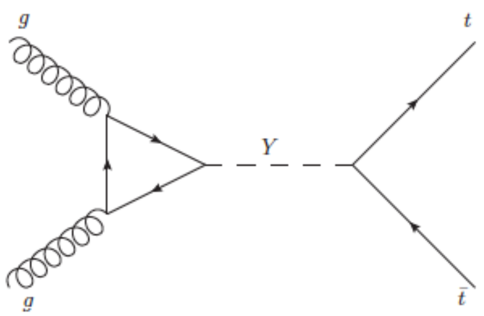
Only one resonance above the $2m_t$ threshold

How bad is the EFT in this case?



Exact and EFT: phase difference

Top-loop induced scenarios: 2HDM



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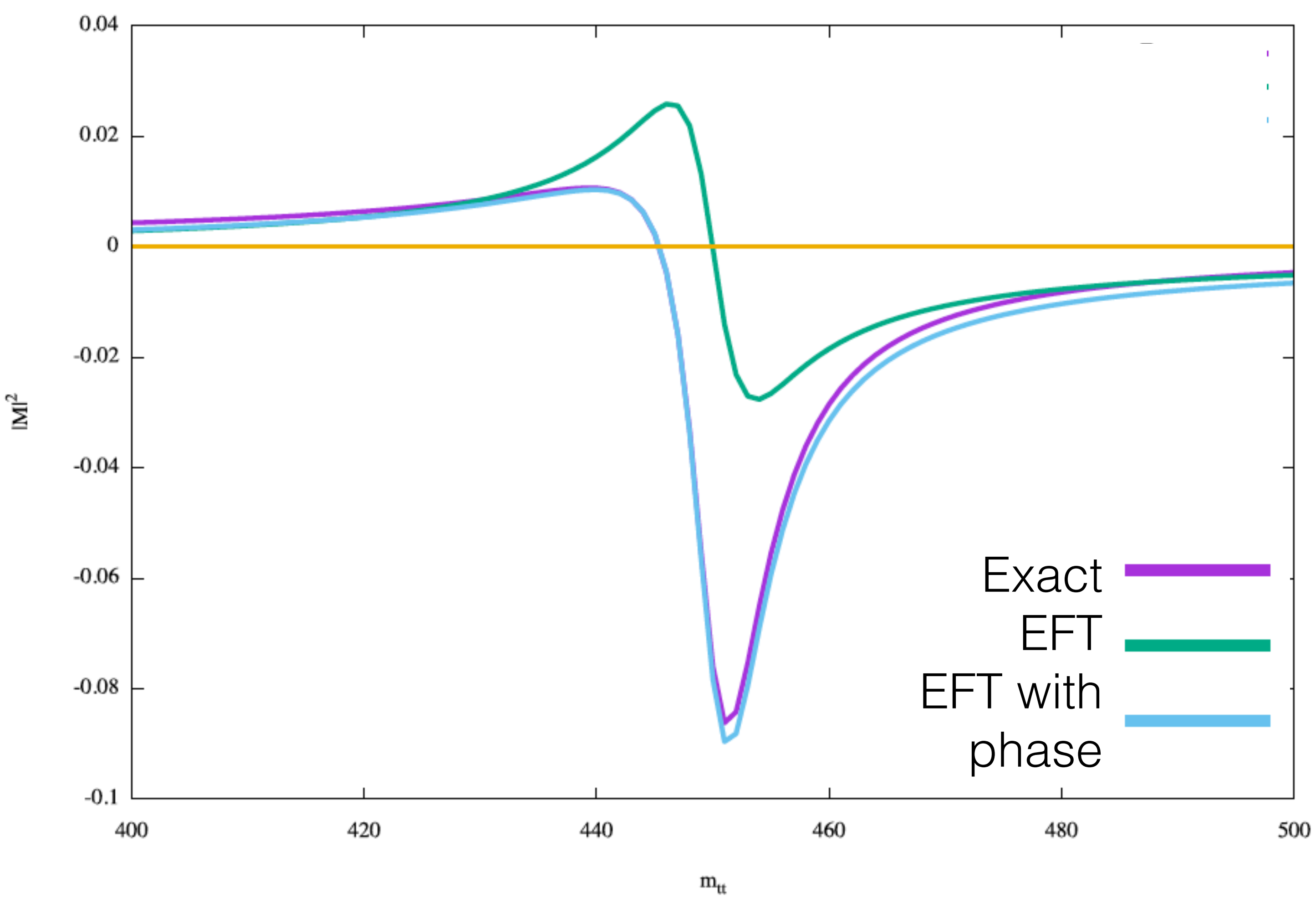
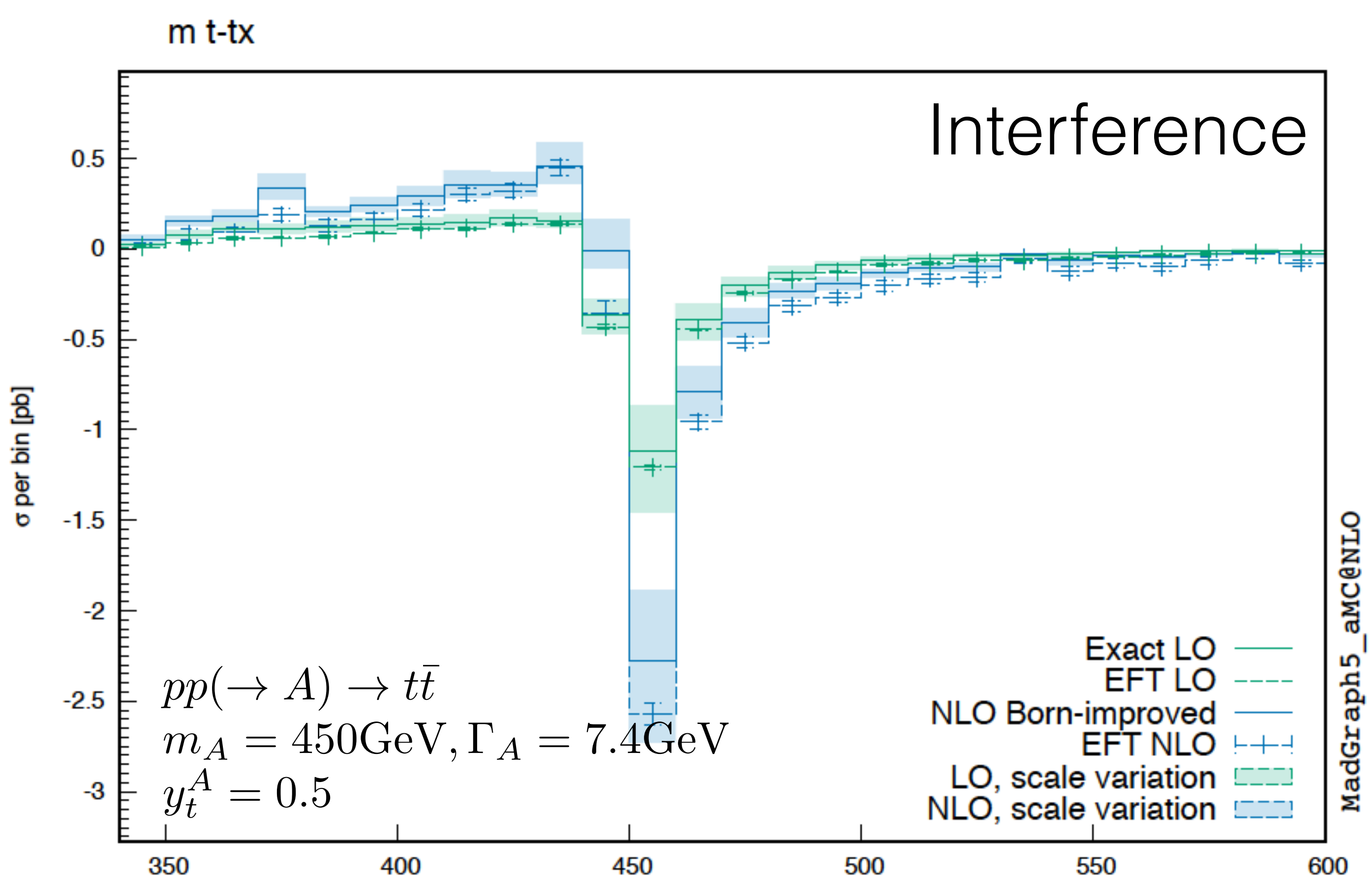


Exact and EFT: phase difference → Introducing a phase

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

Results for the 2HDM

- Can we obtain results beyond LO using the EFT calculation?
- 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



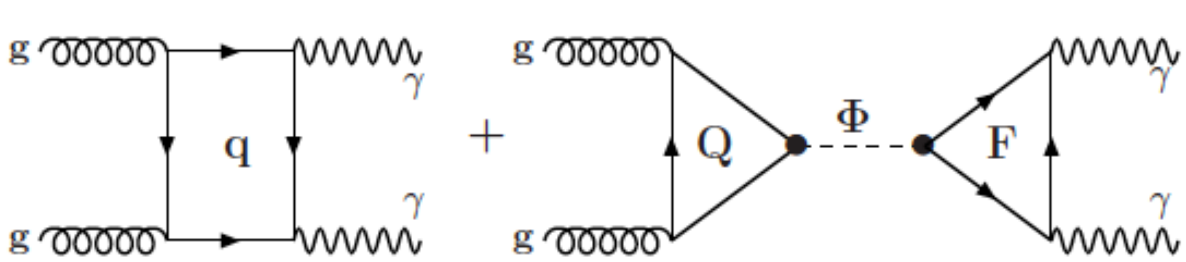
Preliminary

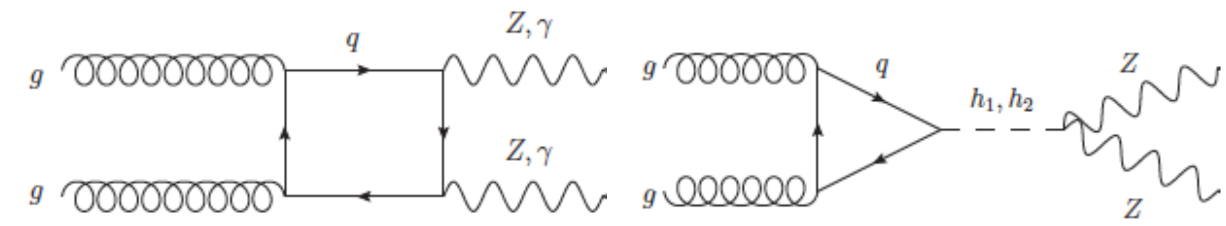
Conclusions-Outlook

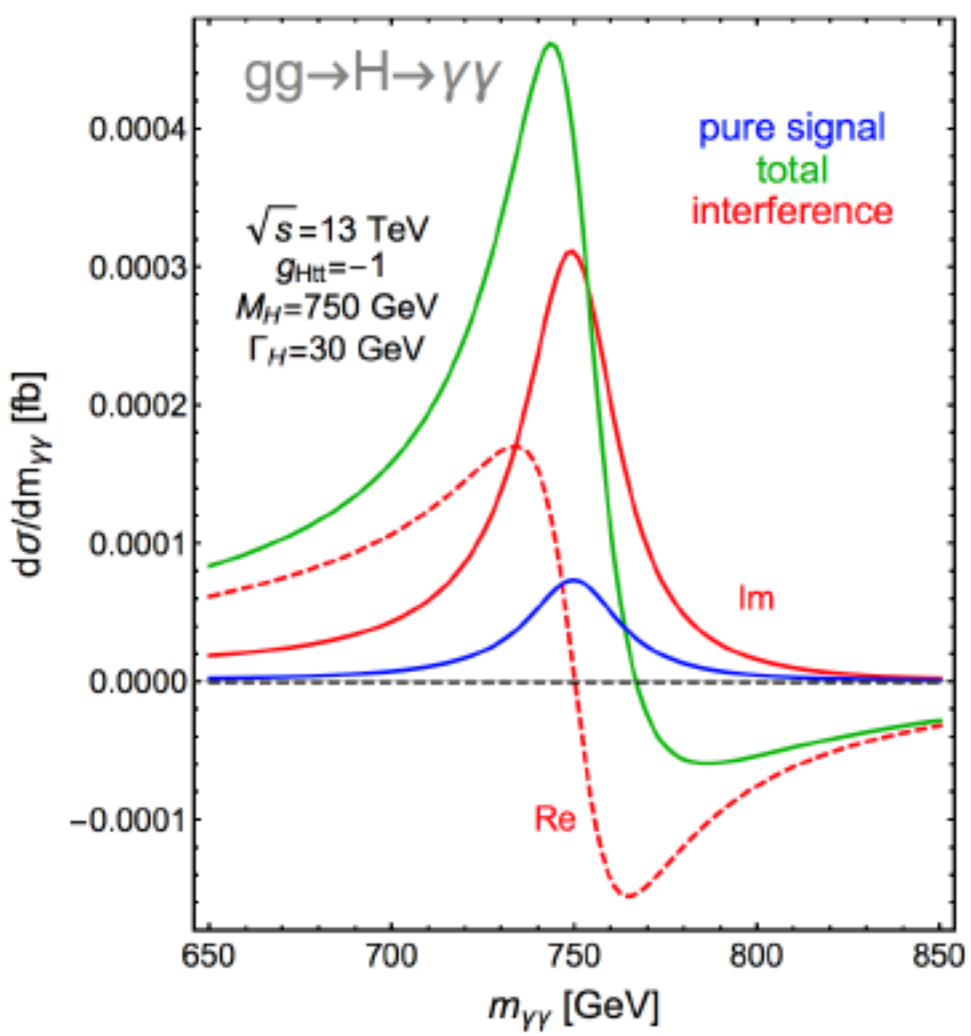
- Top-anti-top resonances: an interesting possibility in various BSM scenarios
- Interference between signal and background changing the line-shape
- Experimental searches demand a good theoretical description for the signal, background and interference
- Interference computed for the first time at NLO in QCD in the EFT limit (heavy quark in loop), taking into account all relevant operators
- 2HDM scenarios also under consideration

Thanks for your attention

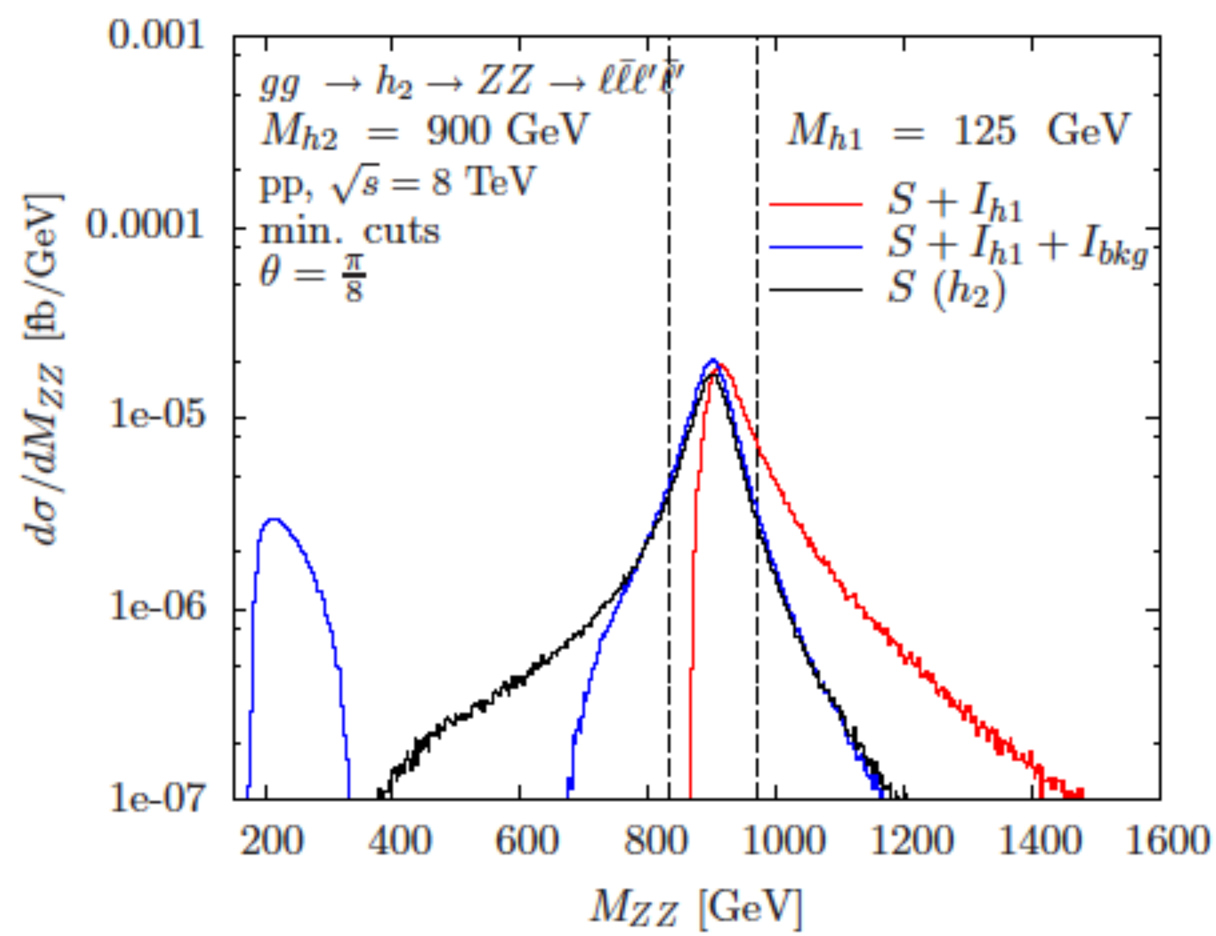
Interference in VV and γγ final states







Ellis, Djouadi, Quevillon arXiv:1605.00542



Higgs Singlet model

O'Brein and Kauer arXiv:1502.04113

See also Englert, Low, Spannowsky arXiv:1502.04678