Heavy scalar lineshape in $t\bar{t}$ final state

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with D. B. Franzosi and E. Vryonidou, in progress

$$\boxed{gg \to H(A) \to t\bar{t}}$$

- Heavy scalars are very common in new physics models (SUSY, 2HDM, Composite Models, etc.)
- Couple to fermions hierarchically, decay dominantly to $t\bar{t}$.
  - $gg \to H \to t\bar{t}$ is an important channel for heavy scalar discovery.

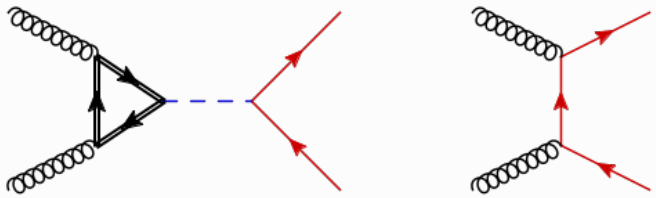
$$\boxed{gg \to H(A) \to t\bar{t}}$$

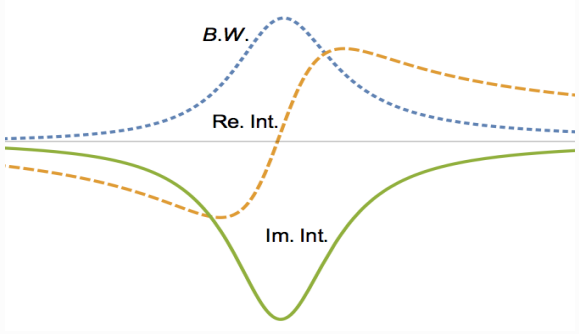
We compute the $t\bar{t}$ lineshape at NLO in QCD with PS, including interference effect, in the EFT limit.

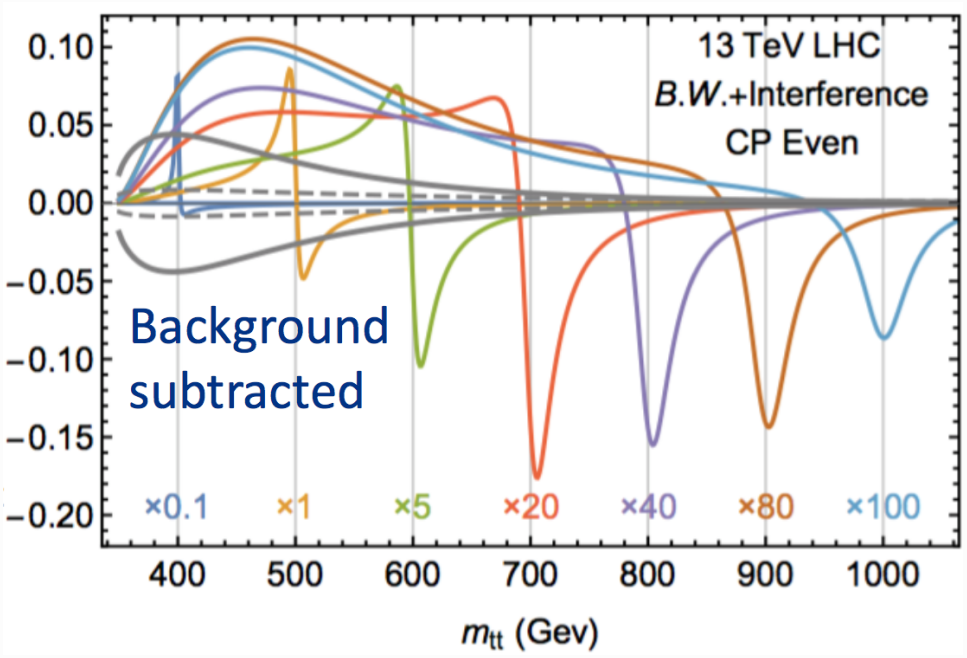
- Physics — lineshapes display interesting features, due to interference and addition phase at ggH.
- Calculation/Monte Carlo — state-of-the-art prediction/simulation for this process. (almost, see talk by H. Yokoya)
- An application of (independent) recent developments in tools for SM/Higgs EFT at NLO.

The $t\bar{t}$ lineshape

Signal+Background



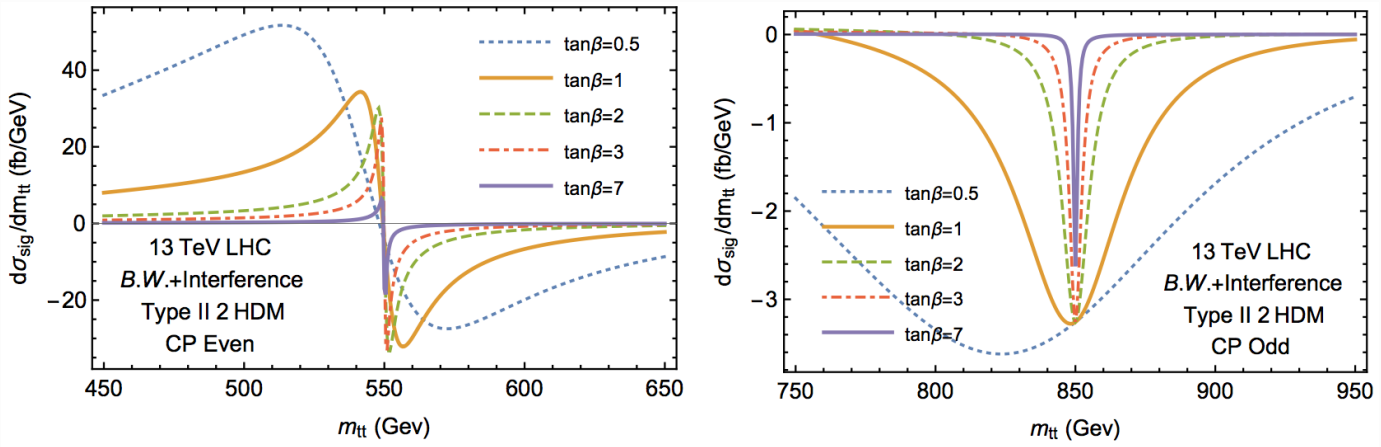




[Carena and Liu], see also [S. Jung et al.]

More lineshapes…

Type II 2HDM



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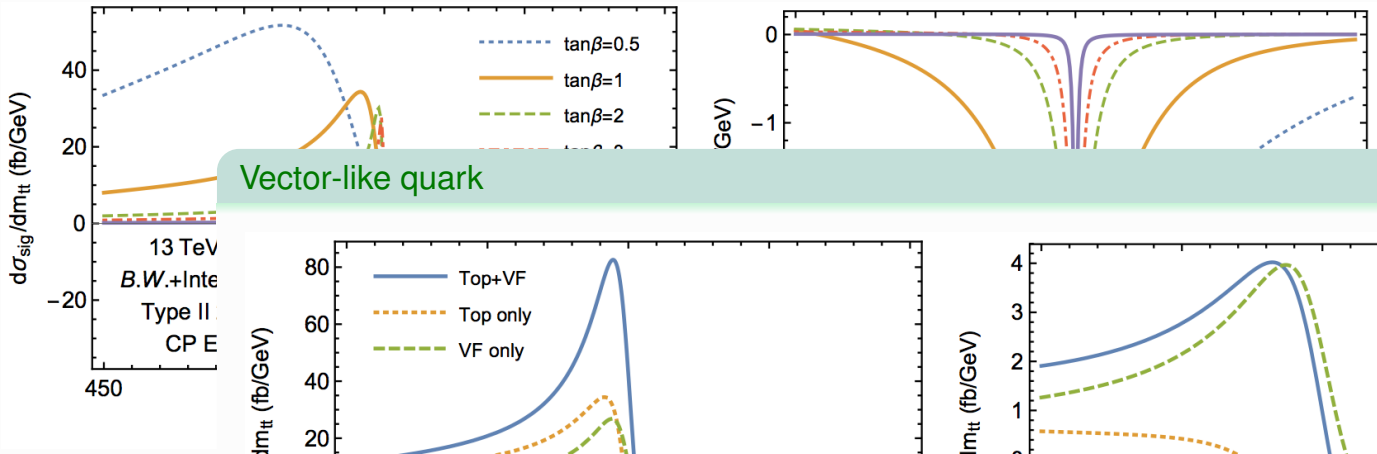
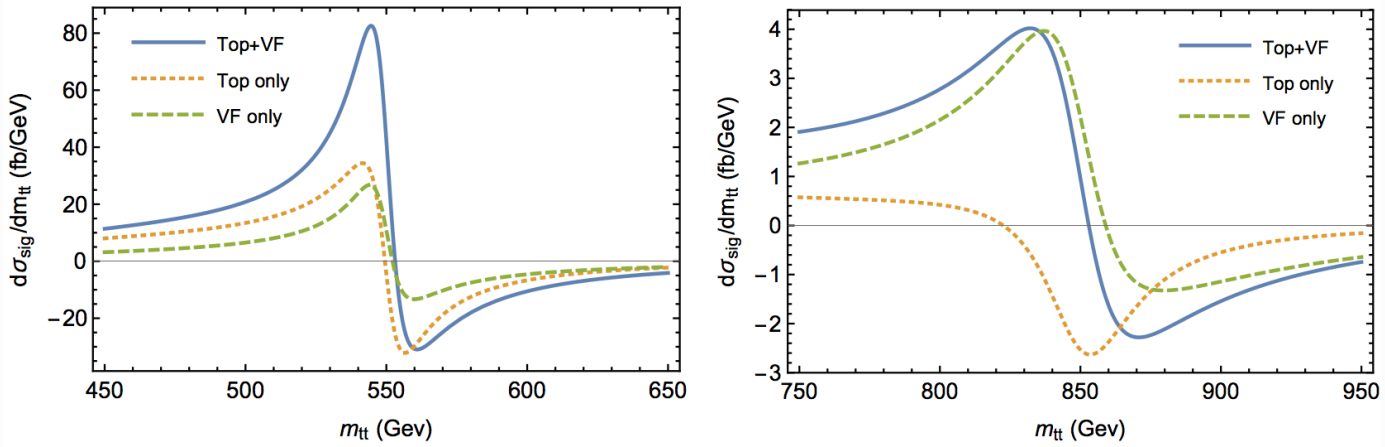


Vector-like quark



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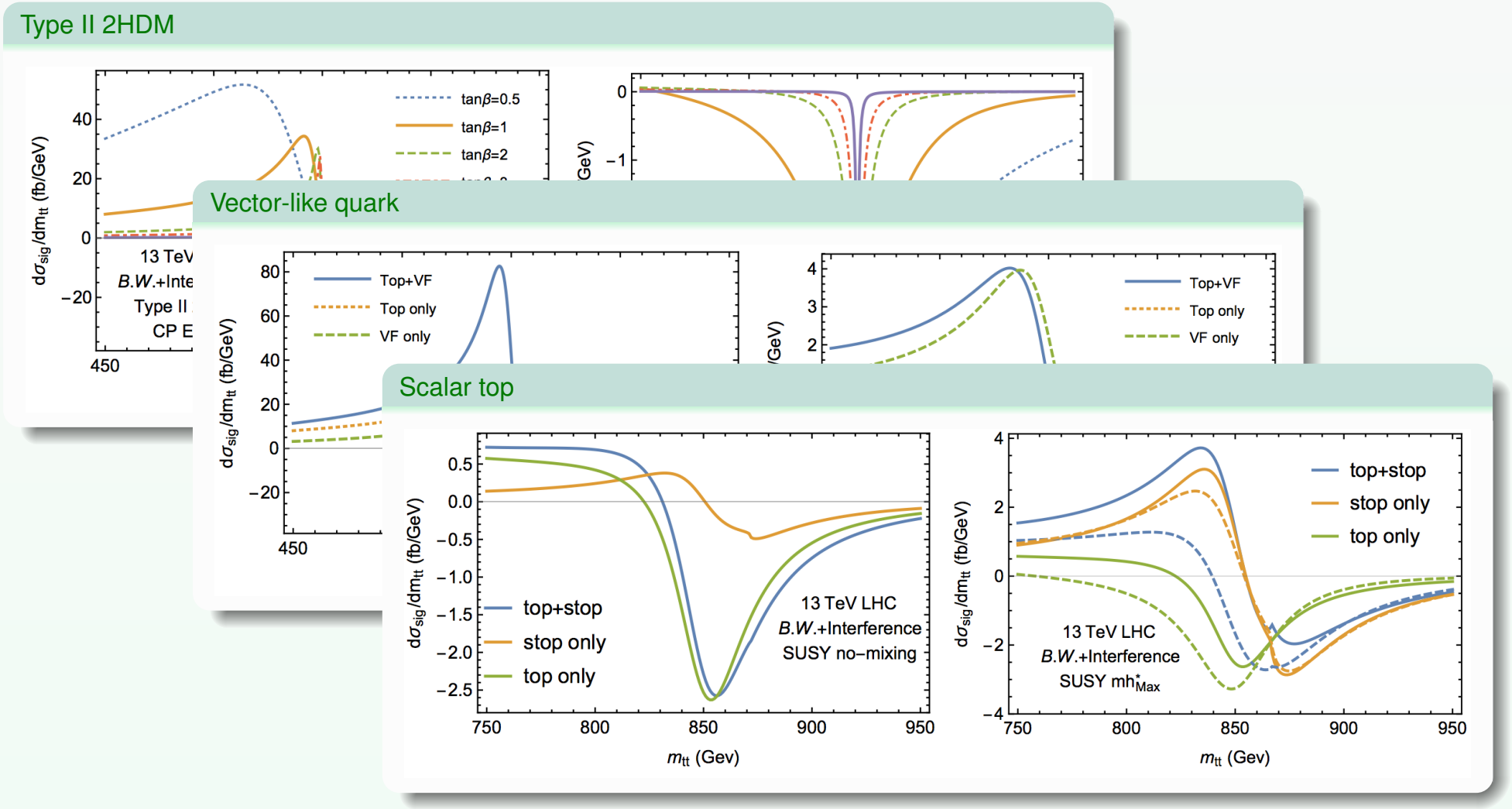


Impact on searching strategy

EXP Experimental search is difficult, due to smearing from parton shower and top reconstruction ($\sim 10\%$), and systematics (4%).

$\Rightarrow$ will need reliable description with QCD correction + PS effects, including interference

so that EXP search can be designed/optimized in a top-down way, for specific lineshapes, to improve sensitivity

[ATLAS-CONF-2016-073]

TH Current status: S(NLO)+B(NLO)+I(LO) is not good enough. ($K_S \approx 2,\ K_B \approx 1.5$)

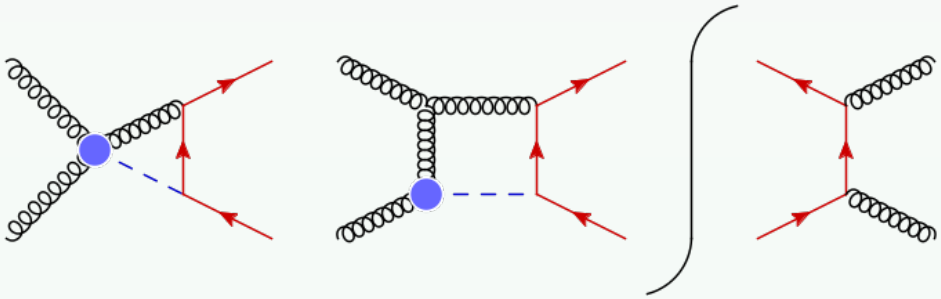
Interference available only through approximate NLO based on

- K-factor rescaling [Hespel, Maltoni, Vryonidou]
- soft-gluon approximation [Bernreuther, Galler, Mellein, Si, Uwer]

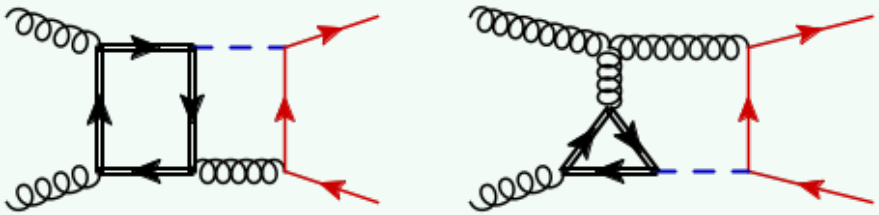
Main difficulty: as a loop-induced process full NLO requires two-loop computation.

NLO predictions for $t\bar{t}$ lineshape

In particular, we need non-factorizable corrections to interference



(which vanishes in signal)
Not easy in the full theory...



Currently the most efficient way is still EFT ($m_{\rm loop} \to \infty$) plus some kind of reweighting ($EFT(NLO) \times \frac{Exact(LO)}{EFT(LO)}$)

Unfortunately, even in EFT limit the complete NLO QCD has not been available.

- Unlike (di-)Higgs production, operator mixing effect makes the problem more complicated.
- Only approximate NLO results are given by:
  - EFT+soft gluon approximation (non-factorisable correction), Born-improved (signal only), FO. [Bernreuther, Galler, Mellein, Si, Uwer]
  - S(exact NLO)+I(LO)$\times\sqrt{K_S K_B}$, +PS [Hespel, Maltoni, Vryonidou]

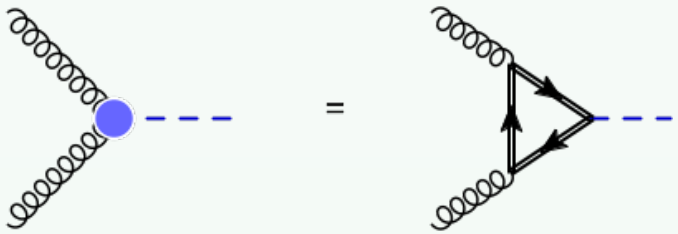
Our goal: Compute the $t\bar{t}$ resonant lineshape at NLO in QCD including interference, by using EFT, without any other approximation.

- Result will be exact in the unresolved case, i.e. heavy VLQ/Stop running in loop, anomaly induced ggA, etc...

Operator mixing

If we do the following:

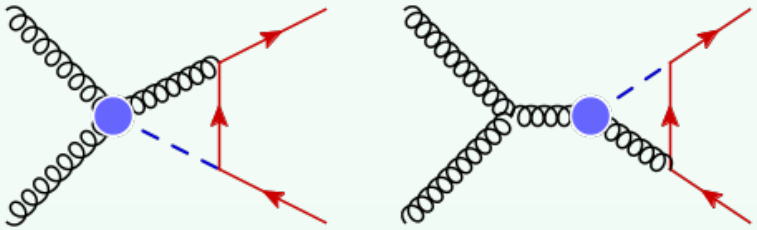
- add $\frac{C_{HG}}{\Lambda} O_{HG} = \frac{C_{HG}}{\Lambda} g_s^2 H G^A_{\mu\nu} G^{A\mu\nu}$ to $\mathcal{L}_{SM}$
- match:



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

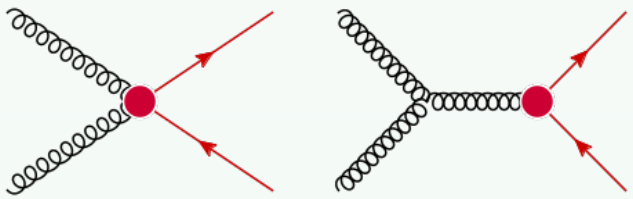
- and compute $pp \to H \to t\bar{t}$ at NLO

Then the non-factorisable diagrams

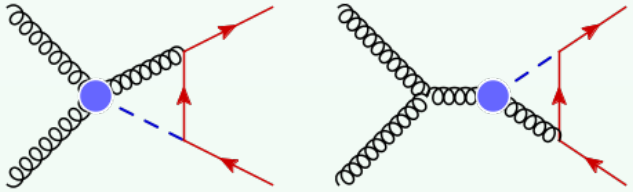


will give rise to UV poles not canceled within the theory.

- Because O_{HG} itself is not renormalizable; it mixes into $O_{tG} = g_s y_t (\bar{t}\sigma^{\mu\nu} T^A t) G^A_{\mu\nu}$, $Z_{tG,HG} = -\alpha_s/2\pi\epsilon_{UV}^{-1}$ (in $\overline{MS}$)
- In SM Higgs production we don't consider O_{tG} because it doesn't play a role in $gg \to h$
- Once we include this operator, we will have



with $\delta C_{tG} = Z_{tG,HG} C_{HG}$, cancelling the poles in



- ...But how to determine δC_{tG}?

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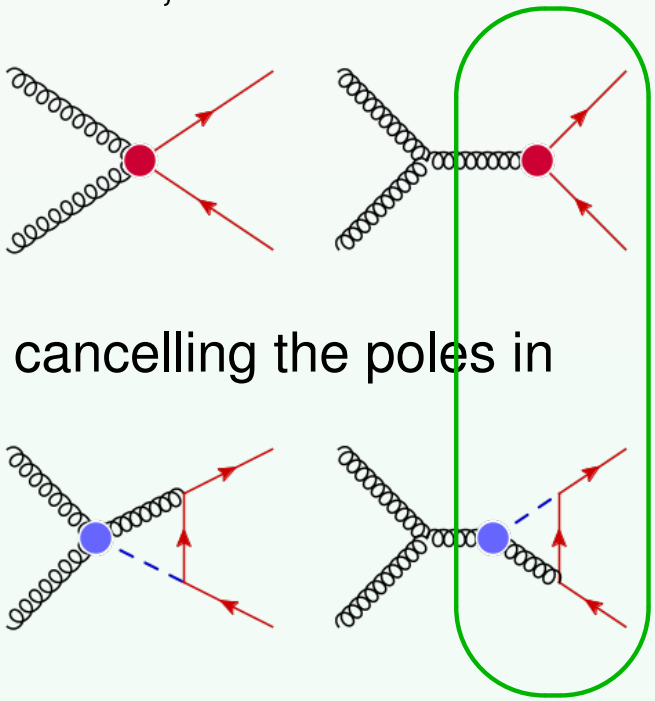

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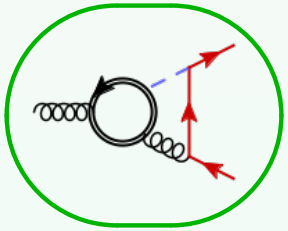

match to Barr-Zee diagram

- ...But how to determine δC_{tG}?

The work flow

We use EFT (of the SM+scalar) in a top-down way

1. Add operators:

$$O_{HG} = g_s^2 H G^A_{\mu\nu} G^{A\mu\nu}, \quad O_{tG} = g_s y_t (\bar{t}\sigma^{\mu\nu} T^A t) G^A_{\mu\nu}$$

2. Matching: (with two-loop *ggH* and Barr-Zee)

$$C_{HG} = -\frac{y_F}{48\pi^2} - \frac{11\alpha_s y_F}{192\pi^3} + \mathcal{O}(\alpha_s^2)$$
$$C_{tG} = -\frac{\alpha_s y_F}{144\pi^3} + \mathcal{O}(\alpha_s^2)$$

3. Running from m_F to $m_H/2$

$$C_{tG}(m_H/2) = C_{tG}(m_F) r^{-\frac{2}{3\beta_0}} + 3C_{HG}(m_F)(1 - r^{-\frac{2}{3\beta_0}})$$
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. . . which is already automated elsewhere

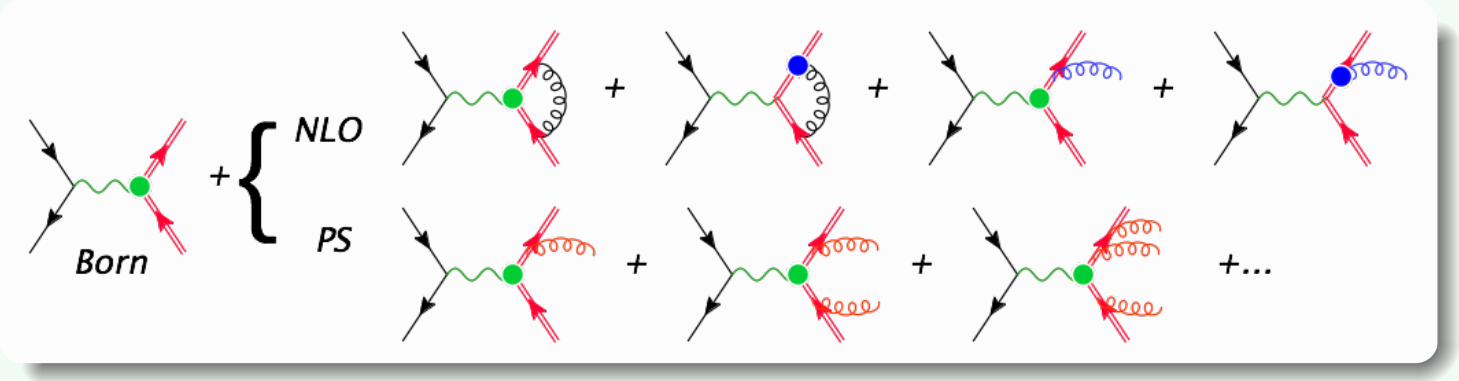
Recent Top-EFT@NLO framework based on MADGRAPH5_AMC@NLO is an ideal to for this.

As documented in [CZ] [Bylund, Maltoni, Tsinikos, Vryonidou, CZ] [D. Franzosi and CZ] [Maltoni, Vryonidou, CZ] [Degrande, Maltoni, Wang, CZ] [Durieux, Maltoni, CZ]

- Just type in MG5

```
MG_DIR>./bin/mg5
MG5_aMC>import model EFT_models
MG5_aMC>generate e- e+ > t t~ EFT=1 [QCD]
MG5_aMC>output some_DIR
MG5_aMC>launch
```

- MG will generate codes for:



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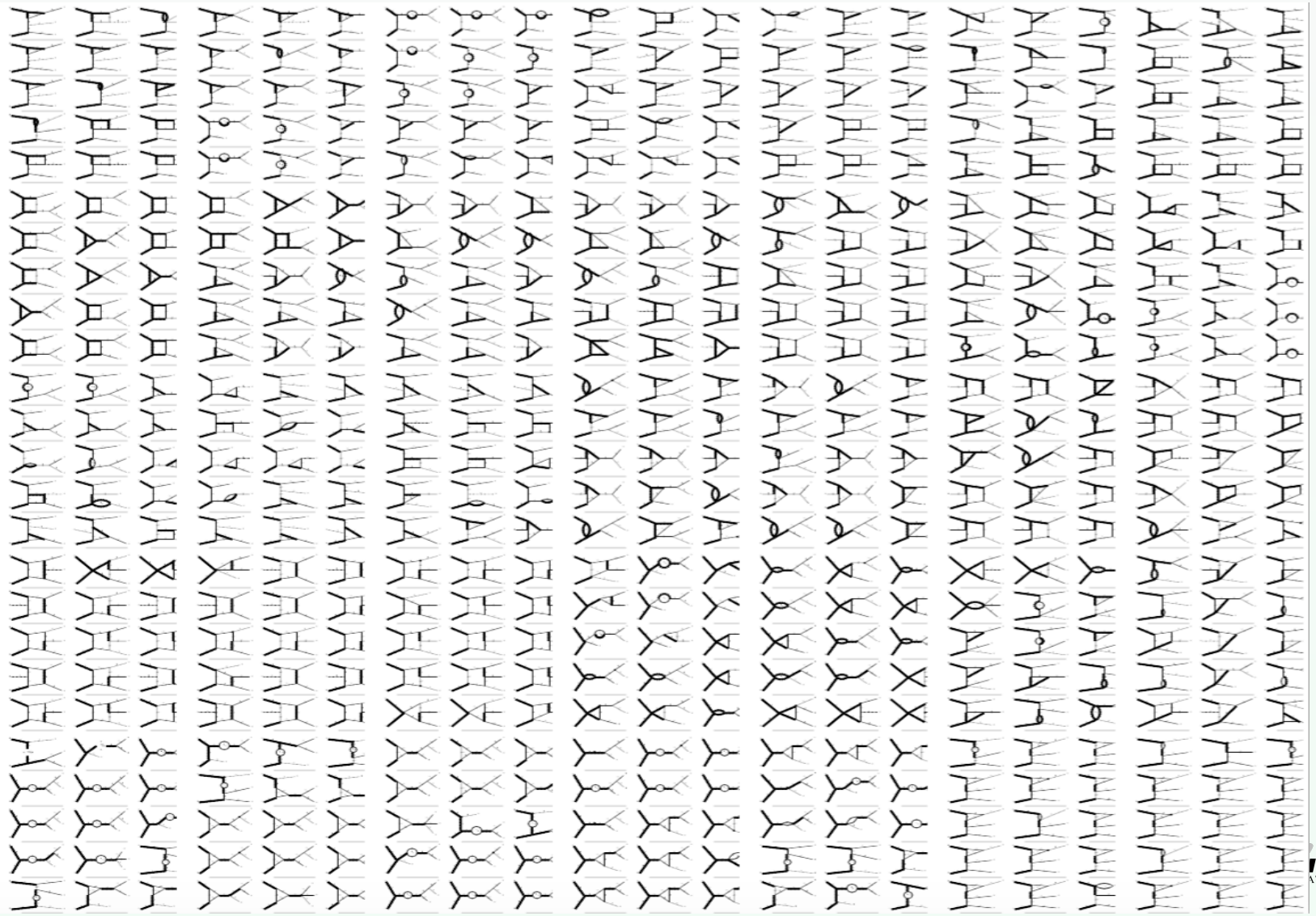


O_{tG}, $O_{\phi G}$, $O_{t\phi}$

- In this implementation we have operators involving $t/H/g$ fields.

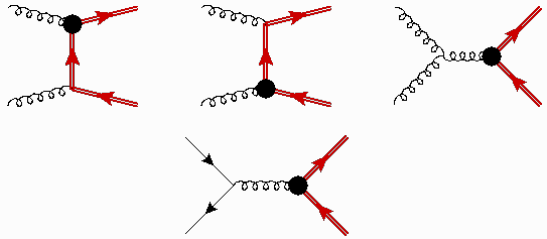
$$O_{t\phi} = y_t^3 \left(\phi^\dagger \phi\right) (\bar{Q}t)\, \tilde{\phi}$$

$$O_{\phi G} = y_t^2 \left(\phi^\dagger \phi\right) G^A_{\mu\nu} G^{A\mu\nu}$$

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

- Key processes:
  - (NLO) $t\bar{t}$ production, constraining O_{tG} [D. Franzosi and CZ]
  - (NLO) $pp \to t\bar{t}H$, all 3 operators [Maltoni, Vryonidou, CZ]
  - (LO) Loop-induced processes:
    - $gg \to H$, all 3 operators
    - $gg \to Hj, HH, \cdots$

$pp \to t\bar{t}$: O_{tG}



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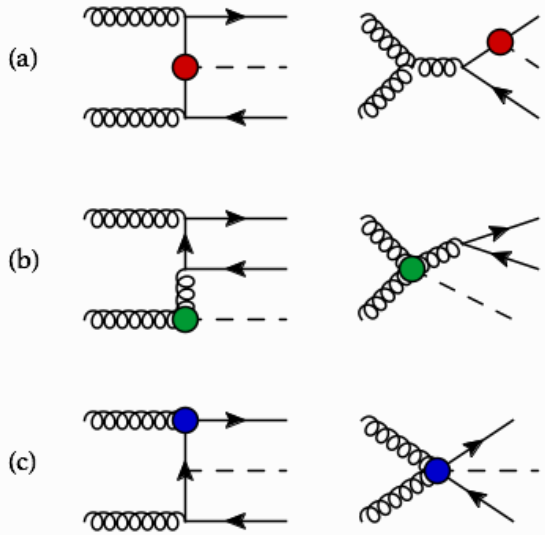

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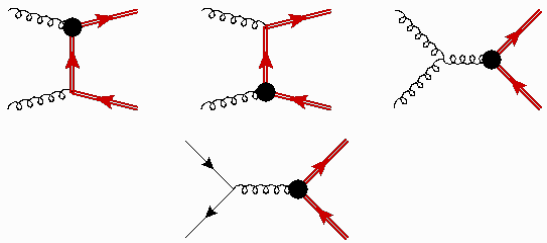

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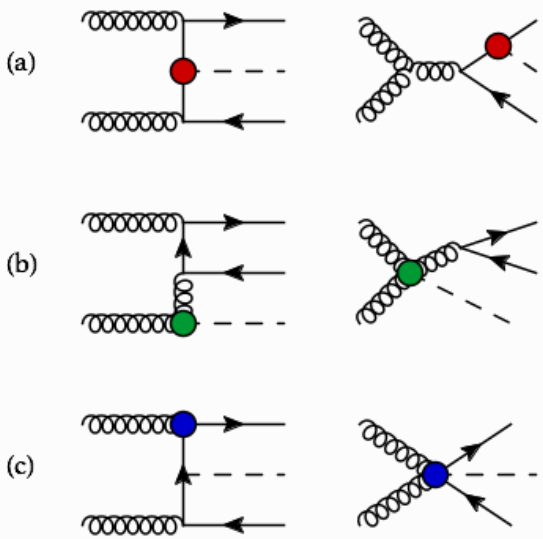

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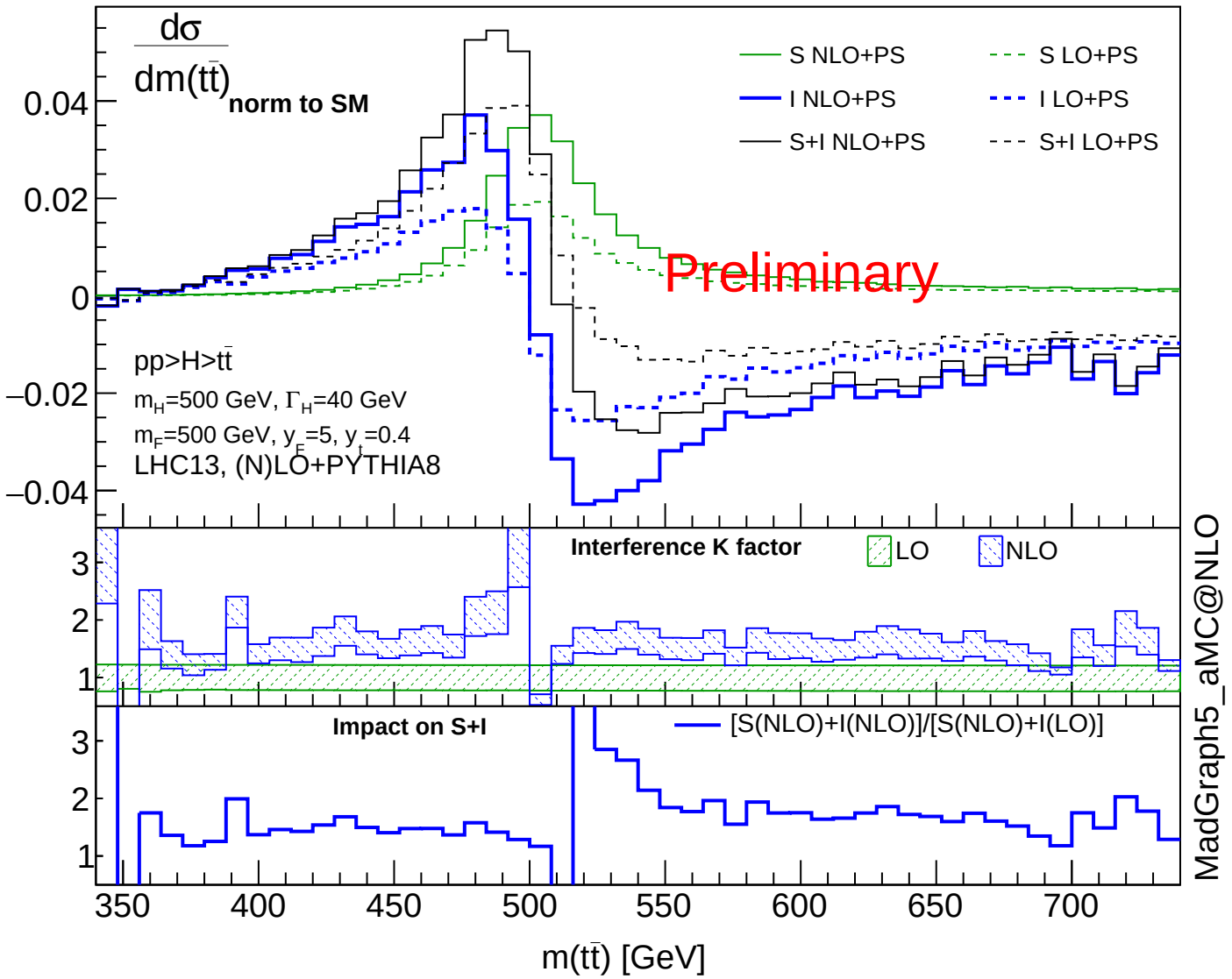
4. ~~...now we need an EFT@NLO calculation.~~ Computer takes care the rest.

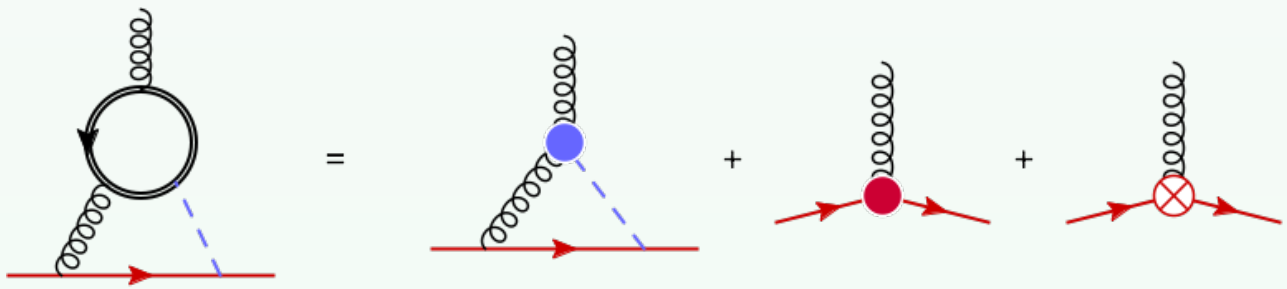

dσ / dm(tt̄) norm to SM
S NLO+PS
I NLO+PS
S+I NLO+PS
S LO+PS
I LO+PS
S+I LO+PS
Preliminary
pp>H>tt̄
m_H=500 GeV, Γ_H=40 GeV
m_F=500 GeV, y_F=5, y_t=0.4
LHC13, (N)LO+PYTHIA8
Interference K factor
LO
NLO
Impact on S+I
[S(NLO)+I(NLO)]/[S(NLO)+I(LO)]
MadGraph5_aMC@NLO
m(tt̄) [GeV]

Summary

- $gg \to H(A) \to t\bar{t}$ is an important channel for heavy scalar discorvery.
- Given the difficulty of EXP search, it is useful to have NLO+PS predcition including the interference.
- This can be done with EFT(+reweighting), in a top down way: matching->running->computing.
- Recently developed simulation tools, namly SMEFT in the top sector at the NLO in QCD automated with MADGRAPH5_AMC@NLO, can be applied to solve the problem.

Backups

- Starting from the full theory, we perform matching with two-loop accuracy.
- In fact, $C_{HG}(= -\frac{y_F}{48\pi^2 m_F})$ receives a $\frac{11\alpha_s}{4\pi}$ correction once $gg \to h$ is matched at two loop.
- Similarly, the same correction now appears in the form of O_{tG}. By matching to a Barr-Zee diagram: ($\mu = \Lambda = m_F$, $C_{HG} = -\frac{y_F}{48\pi^2} + \mathcal{O}(\alpha_s)$)



$$-\frac{g_s^3 y_F y_t}{2304\pi^4 m_F}\left(12\log\frac{m_F}{m_H}+13\right) = -\frac{g_s^3 y_F y_t}{768\pi^4 m_F}\left(\frac{2}{\epsilon}+4\log\frac{m_F}{m_H}+3\right) + C_{tG}\frac{y_t g_s}{m_F} + \frac{g_s^3 y_F y_t}{768\pi^4 m_F}\left(\frac{2}{\epsilon}\right)$$

$$\Rightarrow C_{tG} = -\frac{\alpha_s}{144\pi^3} y_F$$

- Electroweak operators:
  - For testing $tbW/ttZ/tt\gamma$ couplings.
  - Key processes: single top, $pp \to t\bar{t} + V$, and $e^+e^- \to t\bar{t}$.

[CZ] [Bylund, Maltoni, Tsinikos, Vryonidou, CZ]

for ttZ see also: [R. Rontsch and M. Schulze] [R. Rontsch and M. Schulze]

- FCNC operators:
  - For testing $qtg/qtZ/qt\gamma/qtH$ couplings.
  - Key processes: $q + g \to t$, $q + g \to t + Z/\gamma/H$, and $e^+e^- \to tj$

[Degrande, Maltoni, Wang, CZ] [Durieux, Maltoni, CZ]

- Top-Higgs operators:
  - For testing $ttH/gtt(gttH)/ggH$ couplings.
  - Key processes: $pp \to t\bar{t}$, $pp \to t\bar{t} + H$, and loop-induced $gg \to H, Hj, HZ, HH, \cdots$

[D. Franzosi and CZ] [Maltoni, Vryonidou, CZ]

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