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

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with D. B. Franzosi and E. Vryonidou, in progress
Heavy scalars are very common in new physics models (SUSY, 2HDM, Composite Models, etc.)

Couple to fermions hierarchically, decay dominantly to $t\bar{t}$.

- $gg \rightarrow H \rightarrow t\bar{t}$ is an important channel for heavy scalar discovery.
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

Background subtracted

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

Type II 2HDM

- 13 TeV LHC
- B.W.+Interference
- Type II 2 HDM
- CP Even

- 13 TeV LHC
- B.W.+Interference
- Type II 2 HDM
- CP Odd

\( \frac{d\sigma}{dm_{tt}} \) (fb GeV)

- \( m_{tt} \) (Gev)
More lineshapes...

Type II 2HDM

Vector-like quark

Heavy Higgs to \( t\bar{t} \) at NLO

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More lineshapes...

Type II 2HDM

Vector-like quark

Scalar top

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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 ($4\%$).  
⇒ 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  

**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 ($m_{\text{loop}} \to \infty$) plus some kind of reweighting ($EFT(NLO) \times \frac{\text{Exact}(LO)}{EFT(LO)}$)
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]
  - $S(\text{exact NLO})+I(\text{LO}) \times \sqrt{K_S K_B}$, +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 \( L_{SM} \)
- match:

\[
\frac{C_{HG}}{\Lambda} = -\frac{y_F}{48\pi^2 m_F}
\]

- 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 $O_{tG} = g_s y_t (\bar{t} \sigma^{\mu\nu} T^A t) G^A_{\mu\nu}$, $Z_{tG,HG} = -\frac{\alpha_s}{2\pi\epsilon_{UV}}$ (in $\overline{MS}$)

In SM Higgs production we don’t consider $O_{tG}$ because it doesn’t play a role in $gg \rightarrow h$

Once we include this operator, we will have

\[ \delta C_{tG} = Z_{tG,HG} C_{HG}, \]

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

\[ \cdots \text{But how to determine } \delta C_{tG}? \]
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... But how to determine $\delta C_{tG}$?
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 \(m_H/2\)

\[ C_{tG}(m_H/2) = C_{tG}(m_F) r^{-\frac{2}{3\beta_0}} + 3 C_{HG}(m_F) (1 - r^{-\frac{2}{3\beta_0}}) \]
\[ r = \frac{\alpha_s(m_H/2)}{\alpha_s(m_F)}, \quad \beta_0 = 11 - \frac{2}{3} n_f \]

4. ...now we need an EFT@NLO calculation.
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4. ...now we need an EFT@NLO calculation.
... 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 \sim EFT=1 [QCD]
  MG5_aMC>output some_DIR
  MG5_aMC>launch
  ```

- MG will generate codes for:

![Diagram of Born and PS contributions to NLO processes](image)
Recent Top-TAG, an ideal tool for this framework.

As documented in [Degrande, Maltoni, Wang, CZ]

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- or...

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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) \( \bar{t}t \) production, constraining \( O_{tG} \)
  
  \([D. Franzosi and CZ]\)

- (NLO) \( pp \rightarrow \bar{t}tH \), all 3 operators
  
  \([Maltoni, Vryonidou, CZ]\)

- (LO) Loop-induced processes:
  - \( gg \rightarrow H \), all 3 operators
  - \( gg \rightarrow Hj, HH, \cdots \)
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Key processes:

- (NLO) $t\bar{t}$ production, constraining $O_{tG}$
  [D. Franzosi and CZ]
- (NLO) $pp \rightarrow t\bar{t}H$, all 3 operators
  [Maltoni, Vryonidou, CZ]
- (LO) Loop-induced processes:
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4. ...now we need an EFT@NLO calculation. Computer takes care the rest.

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Heavy Higgs to t\(\bar{t}\)bar @ NLO

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$\sigma_{tt}^{\text{NLO}+\text{PS}}$ vs $m_{tt}$

$\frac{d\sigma}{dm_{tt}}$ (norm to SM)

$pp \rightarrow H \rightarrow t\bar{t}$
$m_H = 500 \text{ GeV}, \Gamma_H = 40 \text{ GeV}$

$D = 500 \text{ GeV}, \gamma = 0.4, \lambda = 0.4$

LHC13, (N)LO+PYTHIA8

Interference K factor

Impact on $S+I$

MadGraph5_aMC@NLO

Preliminary
Summary

- $gg \rightarrow H(A) \rightarrow t\bar{t}$ is an important channel for heavy scalar discovery.

- Given the difficulty of EXP search, it is useful to have NLO+PS prediction including the interference.

- This can be done with EFT(+reweighting), in a top down way: matching->running->computing.

- Recently developed simulation tools, namely 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, $pp \to \tt + V$, and $e^+e^- \to \tt$.

For $\ttZ$ see also: [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 $e^+e^- \to tj$.

For $\ttZ$ see also: [R. Rontsch and M. Schulze]

Top-Higgs operators:

- For testing $ttH/gtt(gttH)/ggH$ couplings.
- Key processes: $pp \to \tt$, $pp \to \tt + H$, and loop-induced $gg \to H, Hj, HZ, HH, \cdots$.

For $\ttZ$ see also: [D. Franzosi and CZ] [Maltoni, Vryonidou, CZ]