# Resonant top pair production at NLO in QCD

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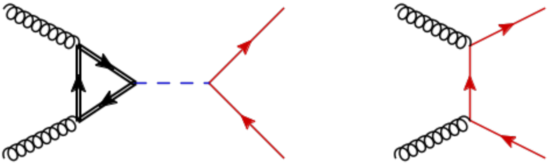
- Motivation
- Computation
- Results

## New heavy (pseudo-)scalar production

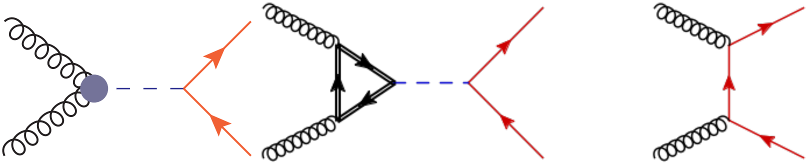
$$pp \to H(A) \to t\bar{t}$$



## Motivation and goal

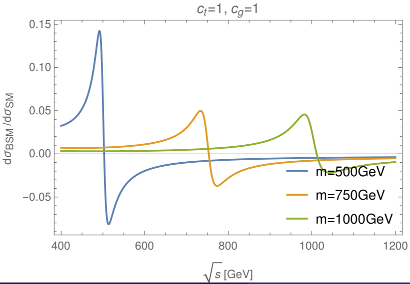
- Top-quark can be a portal to new physics
- QCD correction to QCD SM background ($\sim 50\%$, 1303.6254) and to *pure* signal ($\sim 100\%$, 9504378) large
- Interference large, drastically changing lineshape, known only at LO
- Goal: compute interference at NLO in QCD
- Also: part of program for automation of QCD correction for effective theories (robust gauge-invariant parametrization of new physics)

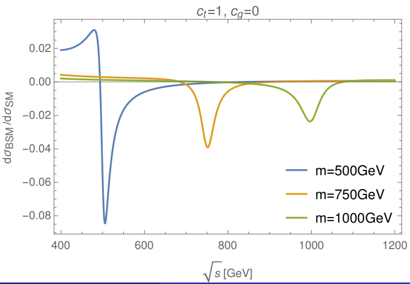
# Interference at LO (Gaemers, Hoogeveen, 84', Dicus, Stange, Willenbrock 94')



$c_g$: unresolved high scale physics, $A^A_{1/2}(\tau)$: resolved loop

$$\left(\frac{d\sigma}{ds}\right)_{INT,A} = -\frac{\alpha_s^2 c_t G_F m^2}{64\pi\sqrt{2}} \log\left(\frac{1+\beta}{1-\beta}\right) \mathrm{Re}\left[\frac{c_g + \sum_f c_f A^A_{1/2}(\tau)}{s - m_A^2 + i m_A \Gamma_A(s)}\right]$$



# Interference at NLO

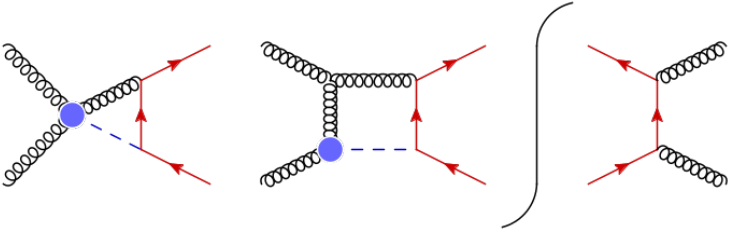
NLO QCD corrections to interference previously computed in an EFT using a soft-gluon approx. (1511.05584) and averaged K-factor (1606.04149)

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

## Non-factorizable corrections

- Vanish for signal correction
- Non-vanishing for interference Signal X Background

We present the exact computation of this effect for the first time in an EFT framework



## Problem: Non-factorizable diagrams generate uncanceled UV poles

- Origin: EFT are renormalizable order-by-order if the full set of higher-dimension operators is considered.
- Missing operator: Chromo-magnetic dipole moment

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

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

## Renormalization in $\overline{MS}$ scheme

- The operators renormalize gluon and top fields, $m_t$, $g_s$...
- as well as the Wilson coefficients (running and mixing), *e.g.* $C_{tG} \to C^{(0)}_{tG} = Z_{tG,i} C_i$, $\delta Z_{tG,HG} = Z_{tG,HG} - 1 = -\frac{\alpha_s}{2\pi} \epsilon^{-1}_{UV}$
- Coefficients run and mix $\frac{dC_i(\mu)}{d \log \mu} = \frac{\alpha_s(\mu)}{\pi} \gamma_{ij} C_j(\mu)$

# Calculation and automation

## Automatic framework based on MadGraph5_aMC@NLO

- Allow automatic generation of events merged with parton shower to compute any time of observable
- Virtual: MadLoop + CutTools, Real: MadFKS
- Previous EFT studies in this framework: $O_{tG}$ in $t\bar{t}$, DBF, Zhang 15', Single top, Zhang 16', $t\bar{t}h$, Maltoni, Vryonidou, Zhang 16' $\cdots$

- Model implemented in the UFO (NLO) 1108.2040 format, UV CT included *by hand*, R2 terms computed via NLOCT package, Degrande
- Complex Mass Scheme to treat resonance widths

# Benchmark scenarios

## Benchmark A

- CP-even scalar $H$ interacting with a heavy new fermion $F$ ($m_F = 500$ GeV, $y_F = 5$).
- $m_H = 500$ GeV, $\Gamma_H = 40$ GeV, $y_t = 0.4$,
- $\frac{C_{HG}}{\Lambda} = -5.11 \times 10^{-5}$ GeV$^{-1}$, $\frac{C_{tG}}{\Lambda} = -1.40 \times 10^{-6}$ GeV$^{-1}$.

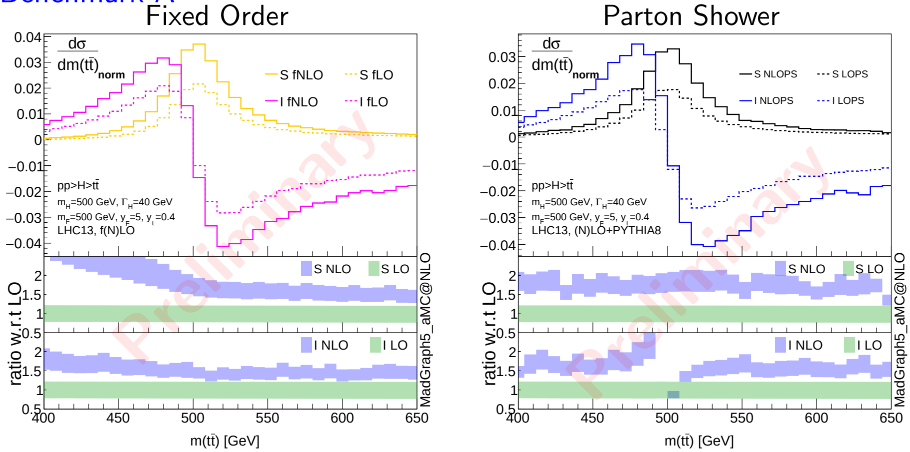
## Benchmark B

- CP-odd $A$ inspired in partial compositeness model (1610.06591).
- $m_A = 1$ TeV, $\Gamma_A = 37.5$ GeV, $\tilde{y}_t = -0.571406$
- $\frac{C_{A\tilde{G}}}{\Lambda} = -2.15308 \times 10^{-5}\text{GeV}^{-1}$, $C_{tG}(1\text{TeV}) = 0(assumed)$

# Results

$\mu_R = \mu_F = \frac{1}{2}\sum_i \sqrt{p^2_{T,i} + m^2_i}$, varying 1/2, 1, 2, $\mu_{EFT} = \frac{m_{H,A}}{2}$
PDF: NNPDF2.3 , PS: PYTHIA8, $m_t = 172.5$ GeV

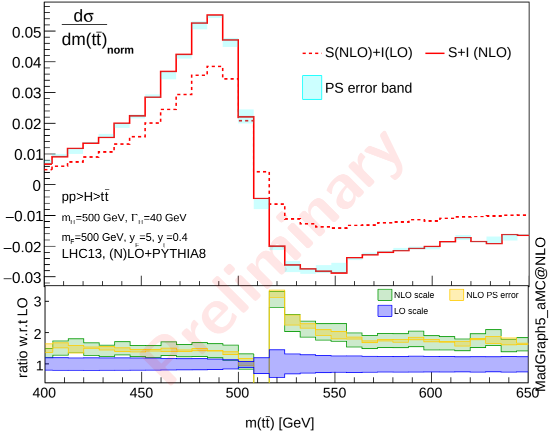
## Benchmark A



# Results: Benchmark A

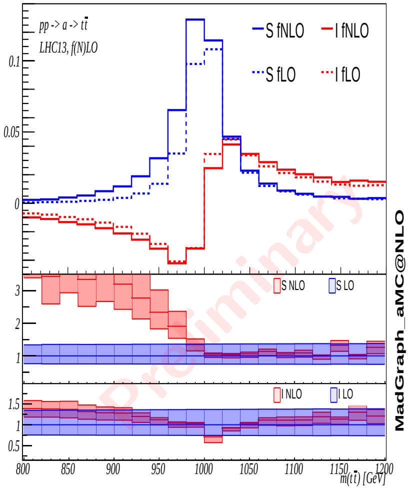
## Parton Shower issue

- Interference has not properly assignment of color flow
- Band given by pure-signal *vs* pure-background color flow

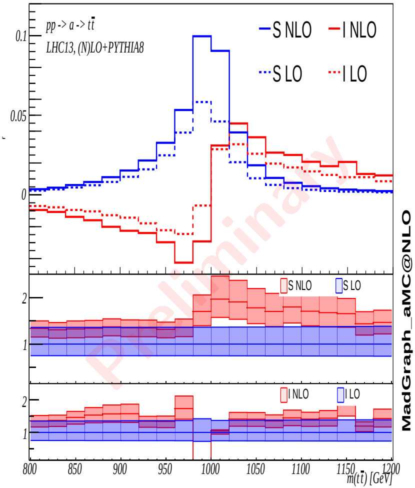


# Results: Benchmark B

Fixed Order



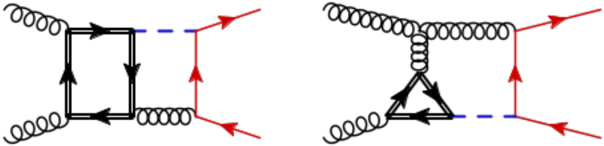

Parton Shower



# Resolved case (top loop): reweighting

## More complicated: 2-loop multiscale problem

Approximate solution: Reweighted Born improved amplitude - factorize out Born contribution and reweight by $w = |M_{exact}|^2/|M_{EFT}|^2$



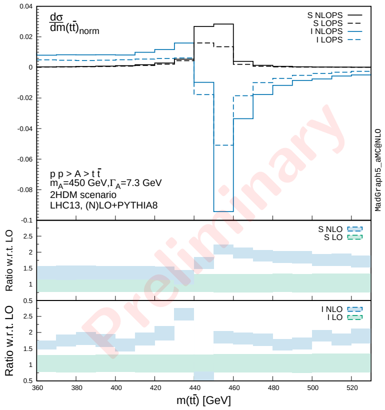
## Benchmark scenarios C: 2HDM

- Fulfill EWPT, LHC Higgs results, searches for heavy scalar particles, unitarity, perturbativity and vacuum stability

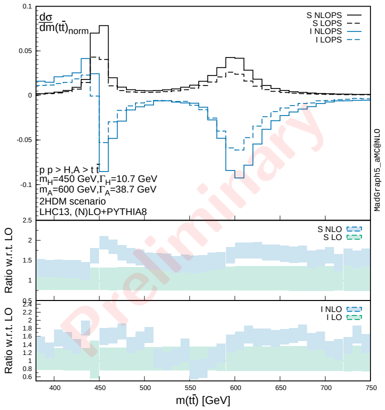
| | Type | $\tan\beta$ | $\sin(\beta-\alpha)$ | $m_H$ | $m_A$ | $m_{H^\pm}$ | $m_{12}^2$ |
|---|---|---|---|---|---|---|---|
| C1 | I | 2.0 | 1.0 | 300 | 450 | 450 | 20000 |
| C2 | II | 0.9 | 1.0 | 450 | 600 | 620 | 10000 |

# Results: Benchmarks C

## C1 PS



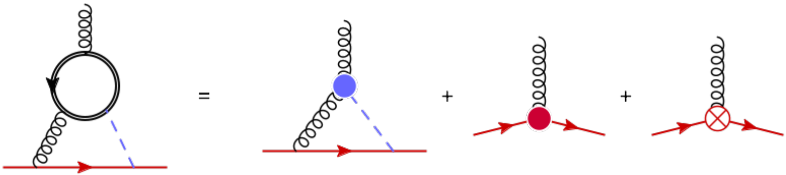

## C2 PS



# Conclusions

- We computed the interference between signal and background in resonant top pair production
- We used an EFT framework implemented via the UFO format, with operator mixing and UV structure (NLO QCD for EFT is an important program for LHC physics)
- The model is loaded in the MadGraph_aMC@NLO framework, which allows fully automatic event generation and parton shower merging
- The resolved case is approximated by a Born-improved reweighting method
- The corrections cannot be fully described by approximations like soft-gluon or K-factors extracted from *pure* background or signal
- It is numerically important and enhances the peak-dip structure of the interference

# Matching (model dependent)




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

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

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

# Running, mixing and renormalization (model independent)

## Running and mixing

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

$$C_i = (C_{HG}, C_{A\tilde{G}}, C_{tG}),\ \gamma = \begin{pmatrix} 0 & 0 & 0 \\ 0 & 0 & 0 \\ -1 & \tilde{y}_t/y_t & 1/3 \end{pmatrix}$$

$$C_i(\mu) = \exp\left(\frac{-2}{\beta_0}\log\frac{\alpha_s(\mu)}{\alpha_s(m_F)}\right)\gamma_{ij}C_j(m_F)$$