Project B2c: Anomalous couplings in the top quark sector - ttH production in SMEFT

Jonathan Hermann, RWTH Aachen University

In collaboration with Gudrun Heinrich, Marius Höfer, Jannis Lang (KIT)
and Małgorzata Worek (RWTH)

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Research Training Group
Physics of the Heaviest
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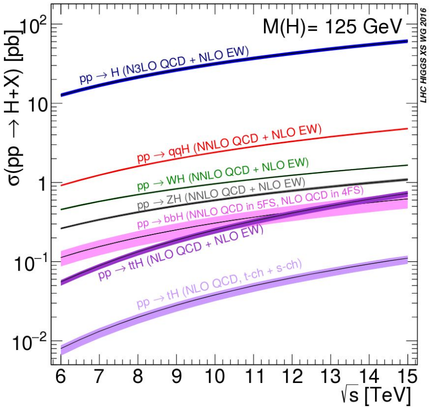
Introduction

ttH production:

- Observed for the first time in 2018, ATLAS '18, CMS'18
- Allows for direct probe of Yukawa interaction
- Top is heaviest SM particle
  → strongest Yukawa coupling

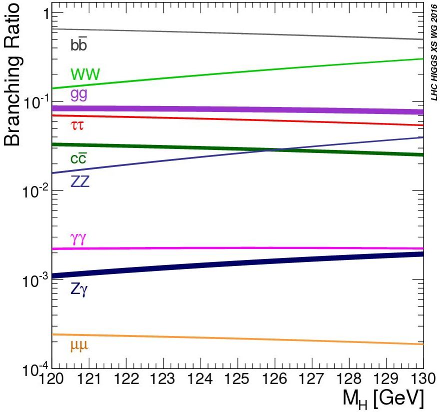
$$y_t = \frac{\sqrt{2} m_t}{v} \sim 1$$

Higgs production:



ttH only 1% of total

Higgs decay:



Main decay channel:
$\mathcal{BR}(H \rightarrow bb) \sim 58\%$

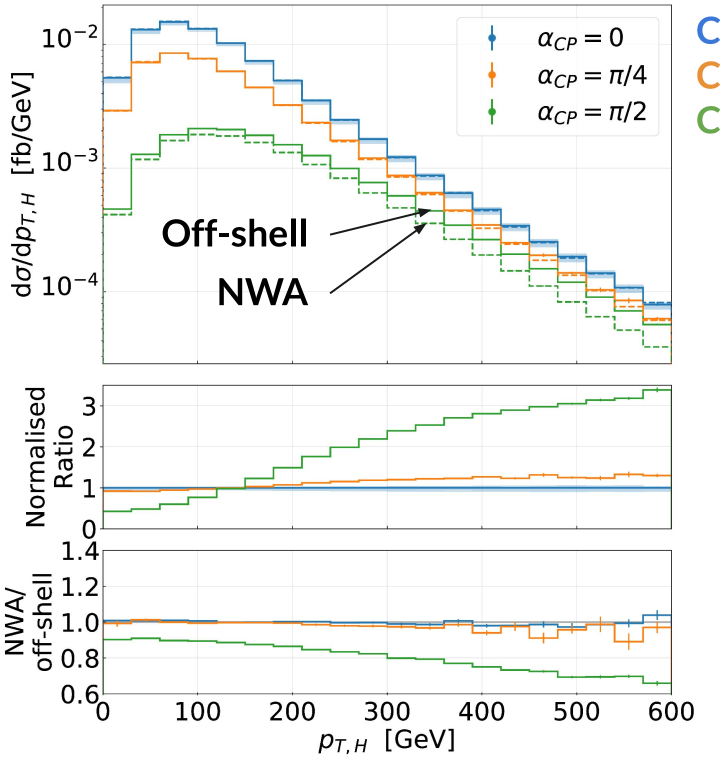
LHC Higgs XS WG '16

Introduction

Anomalous ttH coupling:

- Previous analysis on CP-odd Yukawa coupling
- Large off-shell effects for CP-odd case, even for integrated cross-sections
- Reason: large contributions from single-resonant diagrams

Is the same true for other anomalous couplings, e.g. in SMEFT?



Off-shell

NWA

CP-even

CP-mixed

CP-odd

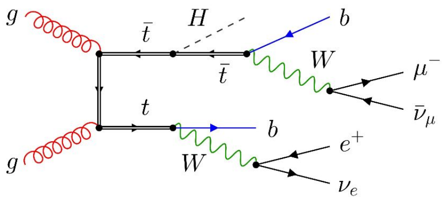
JH, Stremmer, Worek '22

Full off-shell effects

Process: $pp \to e^+ \nu_e \, \mu^- \bar{\nu}_\mu \, b\bar{b} \, H$ at $\mathcal{O}(\alpha_S^2 \alpha^5)$

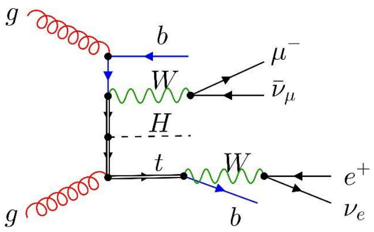
All Diagrams created with FeynGame
Harlander, Klein, Lipp '20

Double resonant

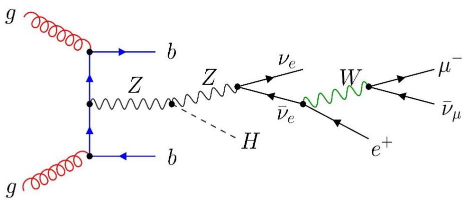


NWA

Single resonant



Non resonant



Off-shell

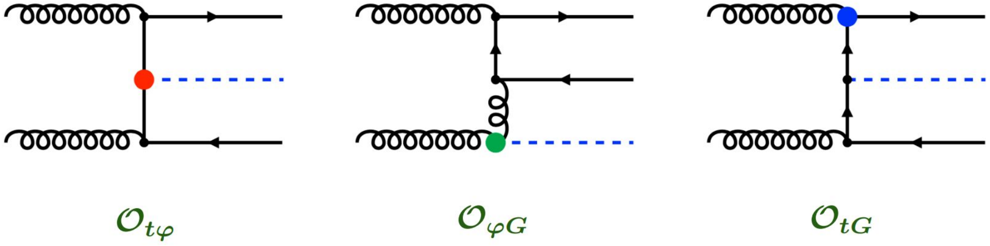
Full off-shell = DR + SR + NR + interference + Breit-Wigner

NWA = DR with on-shell masses $\dfrac{\Gamma}{m} \to 0$

$$\mathcal{O}(\Gamma_t/m_t) \sim 0.8\%$$

State of the art - ttH production

- General framework: SMEFTatNLO *Degrande, Durieux, Maltoni, Mimasu, Vryonidou, Zhang ‘20*
- Here: Stable ttH production in SMEFT at NLO in QCD *Maltoni, Vryonidou, Zhang ‘16*
- Includes three operators: $\mathcal{O}_{t\phi}, \mathcal{O}_{\phi G}$ and $\mathcal{O}_{tG}$
- Additional operators could be included but they are constrained better by other processes



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

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

$$\mathcal{O}_{tG} = y_t g_s \left(\bar{Q}\sigma^{\mu\nu} T^A t\right) \tilde{\phi} G^A_{\mu\nu}$$

State of the art - ttH production

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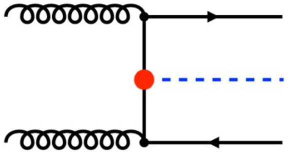
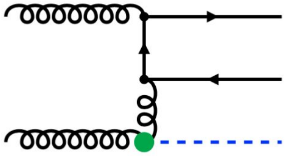
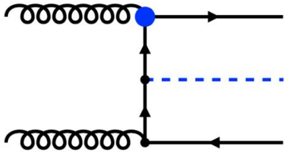


$\mathcal{O}_{t\varphi}$



$\mathcal{O}_{\varphi G}$



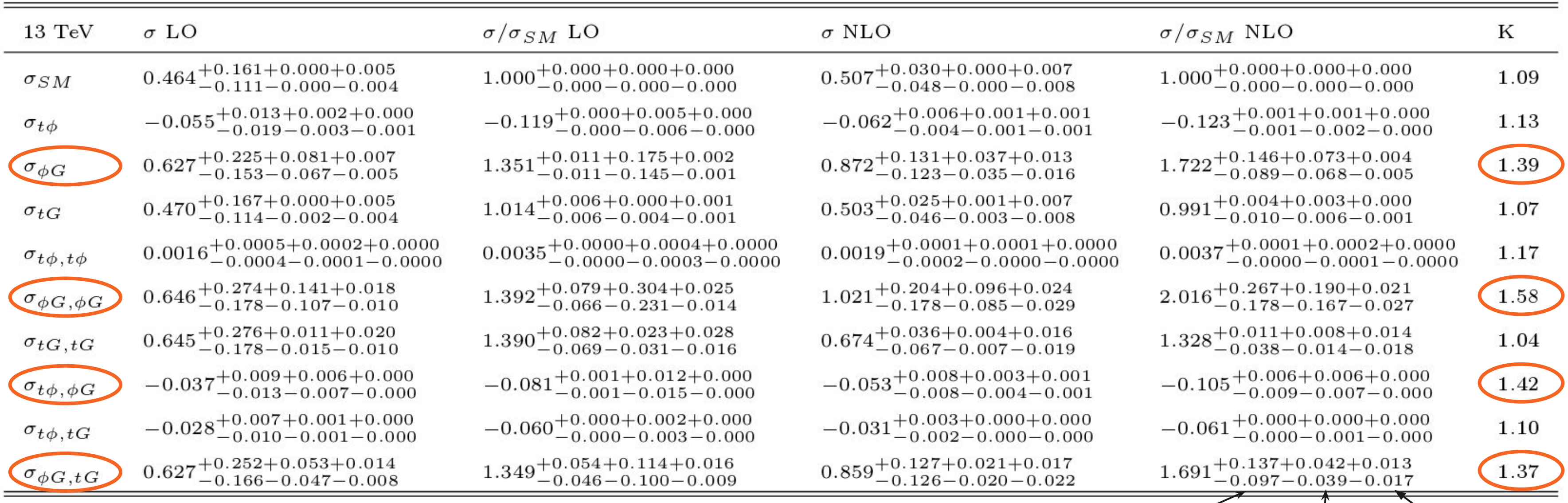
$\mathcal{O}_{tG}$

$$\mathcal{O}_{t\phi} = \cancel{y_t^3} \left(\phi^\dagger\phi\right) \left(\bar{Q}t\right) \tilde{\phi}$$

$$\mathcal{O}_{\phi G} = \cancel{y_t^2} \left(\phi^\dagger\phi\right) G^A_{\mu\nu} G^{A\mu\nu}$$

$$\mathcal{O}_{tG} = \cancel{y_t g_s} \left(\bar{Q}\sigma^{\mu\nu} T^A t\right) \tilde{\phi} G^A_{\mu\nu}$$

State of the art - ttH production



13 TeV	σ LO	σ/σ_{SM} LO	σ NLO	σ/σ_{SM} NLO	K
σ_{SM}	$0.464^{+0.161+0.000+0.005}_{-0.111-0.000-0.004}$	$1.000^{+0.000+0.000+0.000}_{-0.000-0.000-0.000}$	$0.507^{+0.030+0.000+0.007}_{-0.048-0.000-0.008}$	$1.000^{+0.000+0.000+0.000}_{-0.000-0.000-0.000}$	1.09
$\sigma_{t\phi}$	$-0.055^{+0.013+0.002+0.000}_{-0.019-0.003-0.001}$	$-0.119^{+0.000+0.005+0.000}_{-0.000-0.006-0.000}$	$-0.062^{+0.006+0.001+0.001}_{-0.004-0.001-0.001}$	$-0.123^{+0.001+0.001+0.000}_{-0.001-0.002-0.000}$	1.13
$\sigma_{\phi G}$	$0.627^{+0.225+0.081+0.007}_{-0.153-0.067-0.005}$	$1.351^{+0.011+0.175+0.002}_{-0.011-0.145-0.001}$	$0.872^{+0.131+0.037+0.013}_{-0.123-0.035-0.016}$	$1.722^{+0.146+0.073+0.004}_{-0.089-0.068-0.005}$	1.39
σ_{tG}	$0.470^{+0.167+0.000+0.005}_{-0.114-0.002-0.004}$	$1.014^{+0.006+0.000+0.001}_{-0.006-0.004-0.001}$	$0.503^{+0.025+0.001+0.007}_{-0.046-0.003-0.008}$	$0.991^{+0.004+0.003+0.000}_{-0.010-0.006-0.001}$	1.07
$\sigma_{t\phi,t\phi}$	$0.0016^{+0.0005+0.0002+0.0000}_{-0.0004-0.0001-0.0000}$	$0.0035^{+0.0000+0.0004+0.0000}_{-0.0000-0.0003-0.0000}$	$0.0019^{+0.0001+0.0001+0.0000}_{-0.0002-0.0000-0.0000}$	$0.0037^{+0.0001+0.0002+0.0000}_{-0.0000-0.0001-0.0000}$	1.17
$\sigma_{\phi G,\phi G}$	$0.646^{+0.274+0.141+0.018}_{-0.178-0.107-0.010}$	$1.392^{+0.079+0.304+0.025}_{-0.066-0.231-0.014}$	$1.021^{+0.204+0.096+0.024}_{-0.178-0.085-0.029}$	$2.016^{+0.267+0.190+0.021}_{-0.178-0.167-0.027}$	1.58
$\sigma_{tG,tG}$	$0.645^{+0.276+0.011+0.020}_{-0.178-0.015-0.010}$	$1.390^{+0.082+0.023+0.028}_{-0.069-0.031-0.016}$	$0.674^{+0.036+0.004+0.016}_{-0.067-0.007-0.019}$	$1.328^{+0.011+0.008+0.014}_{-0.038-0.014-0.018}$	1.04
$\sigma_{t\phi,\phi G}$	$-0.037^{+0.009+0.006+0.000}_{-0.013-0.007-0.000}$	$-0.081^{+0.001+0.012+0.000}_{-0.001-0.015-0.000}$	$-0.053^{+0.008+0.003+0.001}_{-0.008-0.004-0.001}$	$-0.105^{+0.006+0.006+0.000}_{-0.009-0.007-0.000}$	1.42
$\sigma_{t\phi,tG}$	$-0.028^{+0.007+0.001+0.000}_{-0.010-0.001-0.000}$	$-0.060^{+0.000+0.002+0.000}_{-0.000-0.003-0.000}$	$-0.031^{+0.003+0.000+0.000}_{-0.002-0.000-0.000}$	$-0.061^{+0.000+0.000+0.000}_{-0.000-0.001-0.000}$	1.10
$\sigma_{\phi G,tG}$	$0.627^{+0.252+0.053+0.014}_{-0.166-0.047-0.008}$	$1.349^{+0.054+0.114+0.016}_{-0.046-0.100-0.009}$	$0.859^{+0.127+0.021+0.017}_{-0.126-0.020-0.022}$	$1.691^{+0.137+0.042+0.013}_{-0.097-0.039-0.017}$	1.37

Scale

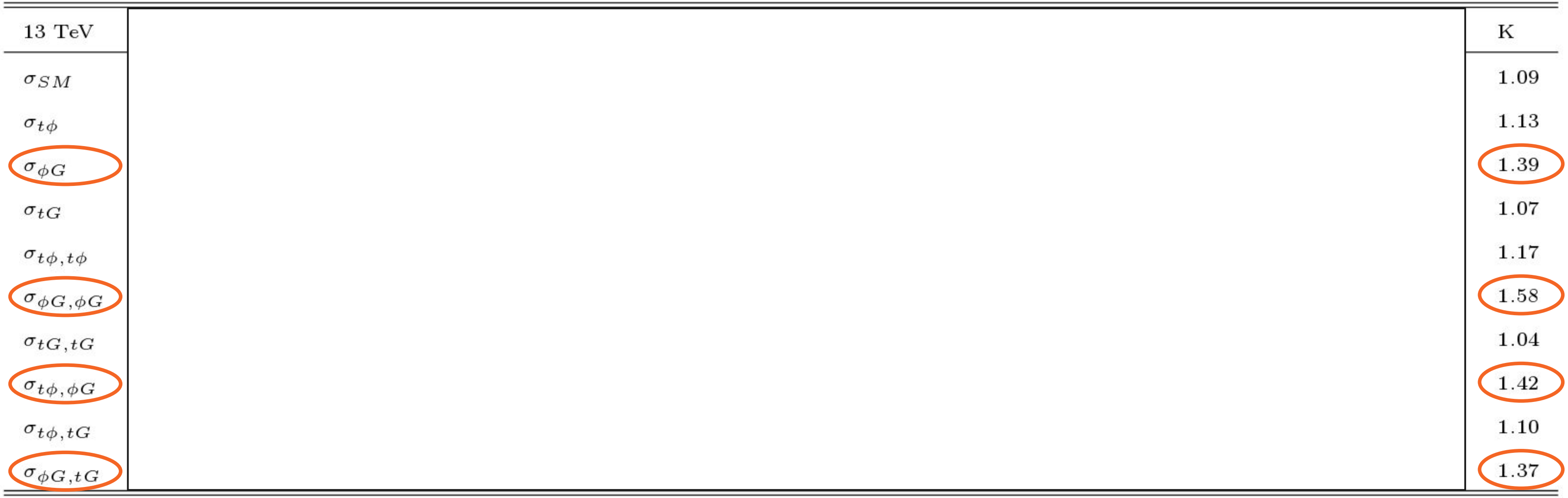
EFT

PDF

$$\sigma = \sigma_{SM} + \sum_i \frac{1\mathrm{TeV}^2}{\Lambda^2} C_i \sigma_i + \sum_{i \leq j} \frac{1\mathrm{TeV}^4}{\Lambda^4} C_i C_j \sigma_{ij}$$

Maltoni, Vryonidou, Zhang '16

State of the art - ttH production



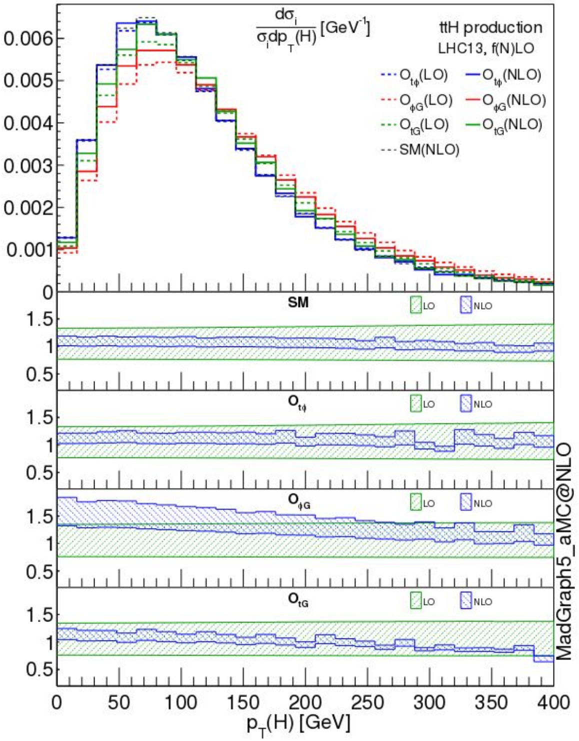
13 TeV	K
σ_{SM}	1.09
$\sigma_{t\phi}$	1.13
$\sigma_{\phi G}$	1.39
σ_{tG}	1.07
$\sigma_{t\phi,t\phi}$	1.17
$\sigma_{\phi G,\phi G}$	1.58
$\sigma_{tG,tG}$	1.04
$\sigma_{t\phi,\phi G}$	1.42
$\sigma_{t\phi,tG}$	1.10
$\sigma_{\phi G,tG}$	1.37

$$\sigma = \sigma_{SM} + \sum_i \frac{1\mathrm{TeV}^2}{\Lambda^2} C_i \sigma_i + \sum_{i \leq j} \frac{1\mathrm{TeV}^4}{\Lambda^4} C_i C_j \sigma_{ij}$$

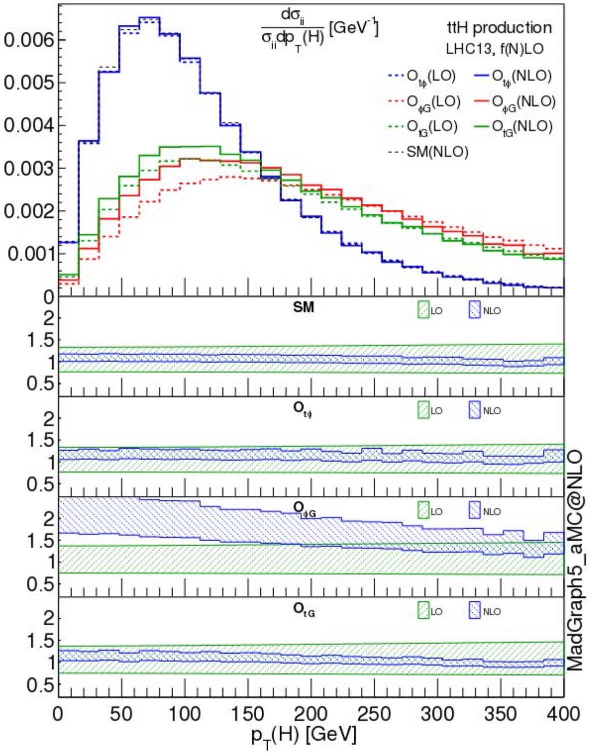
Maltoni, Vryonidou, Zhang '16

State of the art - ttH production

Interference



Squared



Normalised distributions

- SM and $\mathcal{O}_{t\phi}$ very similar but $\mathcal{O}_{\phi G}$ and $\mathcal{O}_{tG}$ have different shapes, particularly for squared contribution
- Large NLO corrections for $\mathcal{O}_{\phi G}$

Maltoni, Vryonidou, Zhang '16

State of the art - ttH production

- **RGE and mixing**

EFT scale

$$\frac{dC_i(\mu_{EFT})}{d\log(\mu_{EFT})} = \frac{\alpha_s}{\pi}\gamma_{ij}C_j(\mu_{EFT}) \qquad \gamma = \begin{pmatrix} -2 & 16 & 8 \\ 0 & -7/2 & 1/2 \\ 0 & 0 & 1/3 \end{pmatrix}$$

- **Renormalisation constants**

In $\overline{MS}$ scheme: $C_i^0 = Z_{ij}C_j, \qquad \delta Z_{ij} = \frac{\alpha_s}{2\pi}\Delta(\mu_{EFT})\frac{1}{\epsilon}\gamma_{ij}$

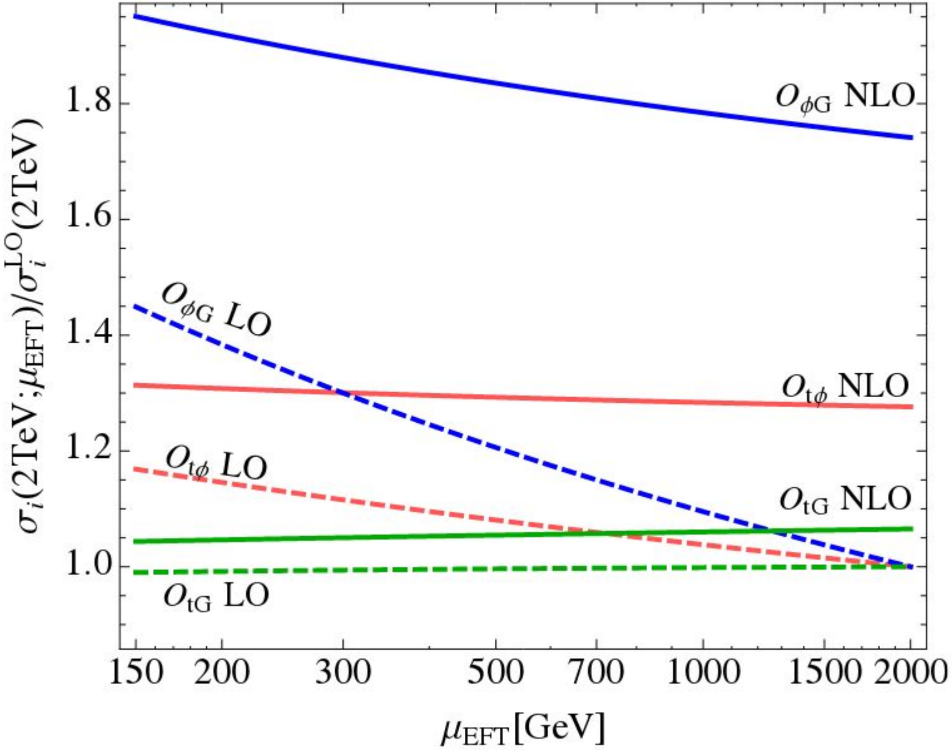
- **Separate running of α_s and EFT**

renorm. scale

$$\Delta(x) \equiv \Gamma(1+\epsilon)\left(\frac{4\pi\mu^2}{x^2}\right)^{\epsilon}$$

Maltoni, Vryonidou, Zhang '16

State of the art - ttH production



RGE corrections

- Evolve Wilson coefficients down from 2 TeV
- RGE corrections significant, but not as large as NLO corrections
- RGE effects reduced at NLO

$$\sigma_i(\mu_0;\mu) = \Gamma_{ji}(\mu,\mu_0)\sigma_j(\mu)$$

$$\Gamma_{ij}(\mu,\mu_0) = \exp\left(\frac{-2}{\beta_0}\log\frac{\alpha_s(\mu)}{\alpha_s(\mu_0)}\gamma_{ij}\right)$$

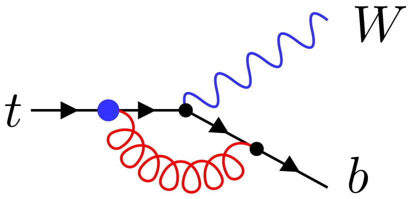
Maltoni, Vryonidou, Zhang ‘16

State of the art - top quark decays

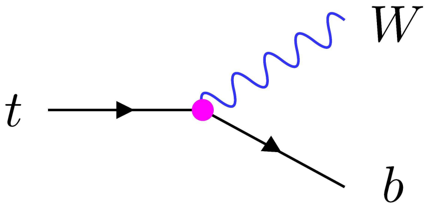
- Analytic results for t → bW and t → blν widths at NLO in QCD in SMEFT

  Zhang '14, *Boughezal, Chen, Petriello, Wiegand '19*
- Can get off-shell top width by rescaling the t → blν result with BR(W→lν)
- Consider contributions from $\mathcal{O}_{tW}$ and $\mathcal{O}_{tG}$ (more in references)

Implemented in **Mathematica** notebook



$\mathcal{O}_{tG}$



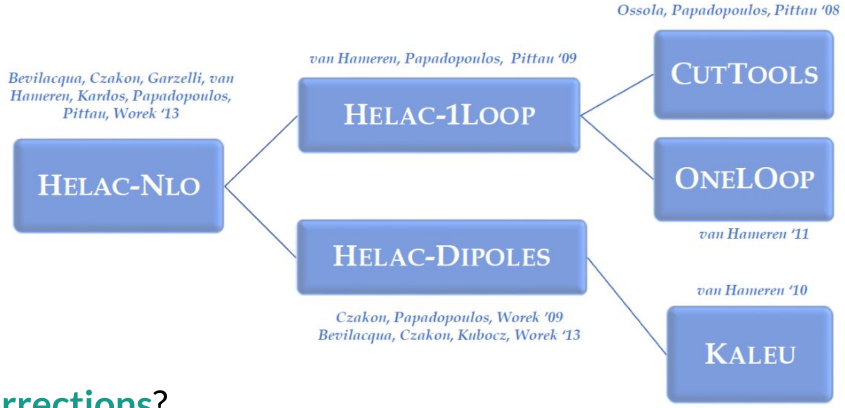
$\mathcal{O}_{tW}$

From *Zhang '14*: $\Gamma^{tot} = [1.311 + 0.158 C_{tW} + \alpha_s\,(-0.11 C_{tW} - 0.04 C_{tG})]\ \mathrm{GeV}$

Status of Project B2c - Goal

Main Goal: $pp \to e^+ \nu_e \, \mu^- \bar{\nu}_\mu \, b\bar{b} \, H + X \text{ at } \mathcal{O}(\alpha_S^3 \alpha^5)$

Provide state-of-the-art predictions for ttH production in **SMEFT** at **NLO in QCD** including **full off-shell effects** using **HELAC-NLO**



Bevilacqua, Czakon, Garzelli, van Hameren, Kardos, Papadopoulos, Pittau, Worek '13

HELAC-NLO

van Hameren, Papadopoulos, Pittau '09

HELAC-1Loop

Ossola, Papadopoulos, Pittau '08

CutTools

OneLOop

van Hameren '11

HELAC-Dipoles

Czakon, Papadopoulos, Worek '09
Bevilacqua, Czakon, Kubocz, Worek '13

van Hameren '10

Kaleu

Questions:

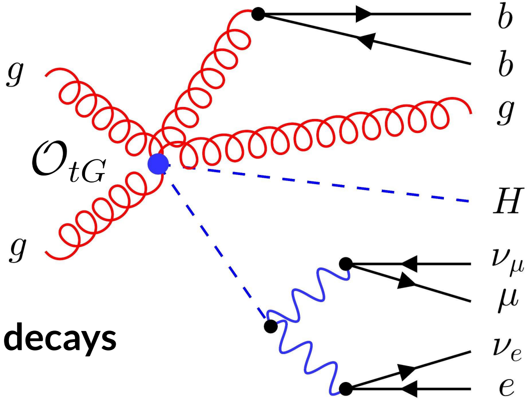
- Can we **reproduce** the results for **stable ttH**?
- What happens if we include **top-quark decays**?
- Which operators are sensitive to **higher-order corrections**?
- How relevant are **off-shell effects**?
- Can we include **additional operators** and / or extend this to **other processes**?

Status of Project B2c - Implementation

- Implemented three operators in HELAC-Dipoles $\mathcal{O}_{t\phi}, \mathcal{O}_{\phi G}, \mathcal{O}_{tG}$
- No way (yet) of generating BSM contributions automatically in HELAC-NLO

  → need to implement all vertices explicitly
- New five- and six-particle vertices appear when including SMEFT operators

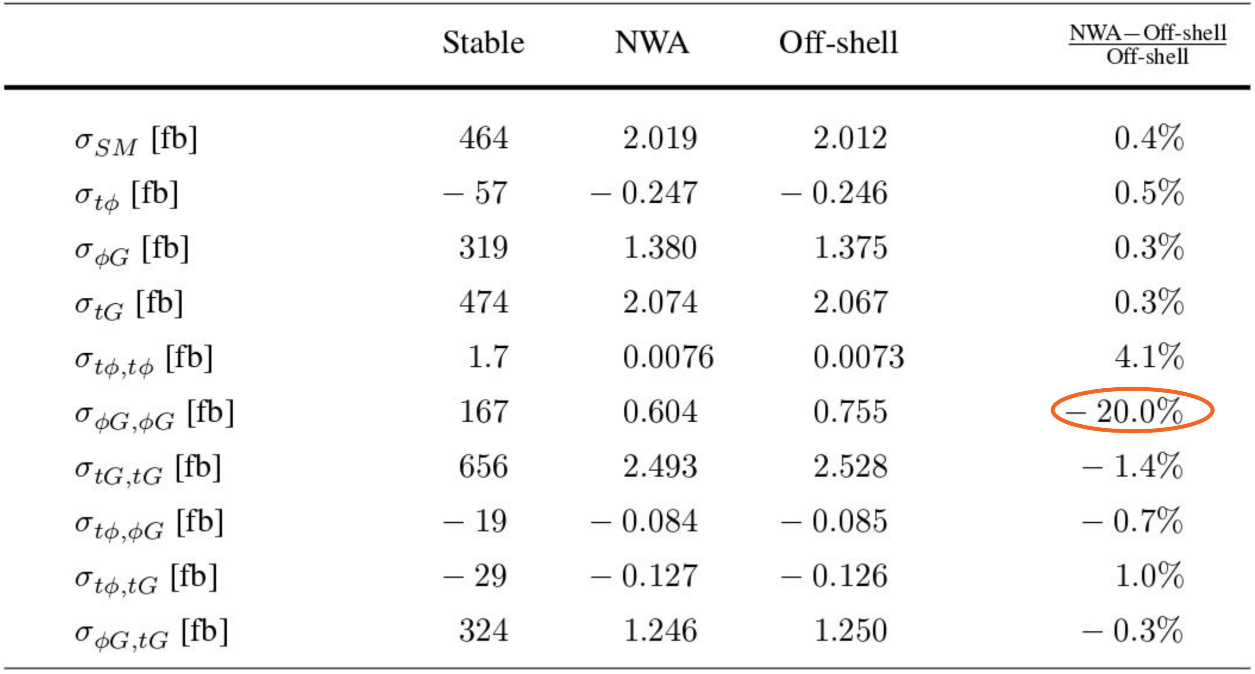
  → extended HELAC-NLO to deal with up to six particle vertices instead of four
- Operators can appear in production and decays
- Cross-checked LO amplitudes with SMEFTatNLO (many processes)
- Reproduced LO cross-sections from *Maltoni, Vryonidou, Zhang '16*



We can produce LO results for ttH production including top-quark decays

Status of Project B2c - ttH with decays at LO

Preliminary!



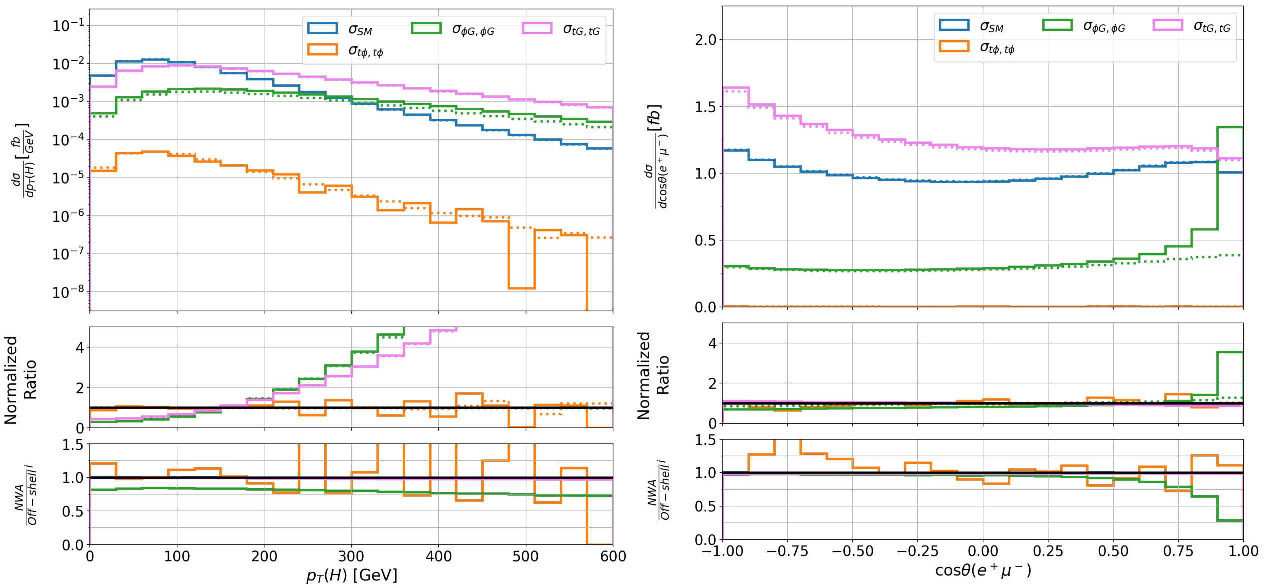
	Stable	NWA	Off-shell	$\frac{\text{NWA}-\text{Off-shell}}{\text{Off-shell}}$
σ_{SM} [fb]	464	2.019	2.012	0.4%
$\sigma_{t\phi}$ [fb]	− 57	− 0.247	− 0.246	0.5%
$\sigma_{\phi G}$ [fb]	319	1.380	1.375	0.3%
σ_{tG} [fb]	474	2.074	2.067	0.3%
$\sigma_{t\phi,t\phi}$ [fb]	1.7	0.0076	0.0073	4.1%
$\sigma_{\phi G,\phi G}$ [fb]	167	0.604	0.755	− 20.0%
$\sigma_{tG,tG}$ [fb]	656	2.493	2.528	− 1.4%
$\sigma_{t\phi,\phi G}$ [fb]	− 19	− 0.084	− 0.085	− 0.7%
$\sigma_{t\phi,tG}$ [fb]	− 29	− 0.127	− 0.126	1.0%
$\sigma_{\phi G,tG}$ [fb]	324	1.246	1.250	− 0.3%

Integrated cross-sections

- Ratio between stable ttH production and NWA / Off-shell is around 0.44%
- Only small off-shell effects for most cross-sections
- Large effects in $\sigma_{\phi G,\phi G}$ come from bbHH production, can be suppressed by invariant mass cut $|M_{4l} - m_H| > X$

Status of Project B2c - ttH with decays at LO

Preliminary!


Squared

Squared

Off-shell = solid, NWA = dotted

Differential distributions

- Similar behaviour as for stable top quarks, i.e. SM and $\sigma_{t\phi,t\phi}$ very similar but $\sigma_{\phi G,\phi G}$ and $\sigma_{tG,tG}$ have different shapes
- Large off-shell effects for $\sigma_{\phi G,\phi G}$
- Very small statistic for $\sigma_{t\phi,t\phi}$

Status of Project B2c - Towards NLO

Real part:

- LO implementation in HELAC-Dipoles → get real part immediately
- Cross-checked poles with SMEFTatNLO
- Confirmed α_{max} independence (parameter for dipole phase-space restriction in Catani-Seymour subtraction scheme)

Virtual part:

- Use HELAC-1LOOP or external program for 1-Loop amplitude calculation
- We now have interfaces between HELAC-NLO and GoSam (JH) / Recola (Daniel Stremmer)
- SM results have been cross-checked at amplitude and cross-section level
- **But:** problems going to SMEFT for all codes

Status of Project B2c - Towards NLO

HELAC-1LOOP:

- No UFO-interface → need to add counterterms and R2 terms by hand

GoSam:

- Has a UFO interface → can simply import SMEFTatNLO model
- Fairly slow and memory intensive → can realistically only do stable ttH in SMEFT

Recola / Rept1l:

- Has a UFO interface → can simply import SMEFTatNLO model
- Rept1l can do automatic renormalisation of LO UFO models
- Problems actually running Rept1l, missing documentation, broken examples

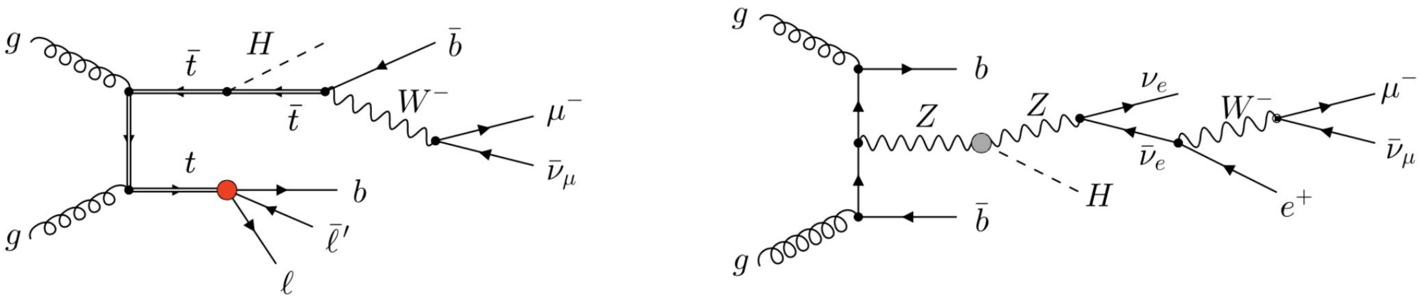
Summary

- **Goal**: ttH production in SMEFT at NLO in QCD with top quark decays and off-shell effects
- **State of the art**:
  - Stable ttH production at NLO in QCD
  - Top quark decays at NLO in QCD

  Only exist separately
- **Current status of project B2c:**
  - We have **LO results** for ttH production with top quark decays (Off-shell and NWA)
  - **Real part** of NLO calculation is implemented and cross-checked
- **Missing pieces for analysis**:
  - Find solution for **virtual part**
  - **Renormalisation** of SMEFT operators & RGEs
  - Implementation of $\mathcal{O}_{tW}$

Future plans

- We are at the very **beginning of this project** and have many more things to do
- Include **additional operators**, in particular four-fermion operators



- Analyse **additional processes**, ttH is only supposed to be the first step
- Create **UFO interface** for HELAC-NLO

Thank you for your attention!

Backup

Dipole phase-space restriction

Idea: Restrict phase space of dipole integration to the relevant region, i.e. the region where soft and collinear divergences can occur

Example: final state splitting of particle (ij) into i and j with k as final state spectator

$$\int_{m+1} d\sigma^A(\alpha_{\max}) = \sum_{k\neq i,j} \int d\Gamma^{(m+1)} \mathcal{D}_{ij,k} \Theta(y_{ij,k} < \alpha_{\max}) J_m$$

where $y_{ij,k} = \dfrac{p_i p_j}{p_i p_j + p_j p_k + p_k p_i}$ → small when i or j soft or when i & j are collinear

Nagy, Trócsányi ‘99, Nagy ‘03, Bevilacqua, Czakon, Papadopoulos, Pittau, Worek ‘09