NATIONAL CENTRE FOR
SCIENTIFIC RESEARCH "DEMOKRITOS"
INSTITUTE OF NUCLEAR AND PARTICLE PHYSICS

A NLO study of $pp \to t\bar{t}H$ with decaying tops in SMEFT

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NCSR "Demokritos"

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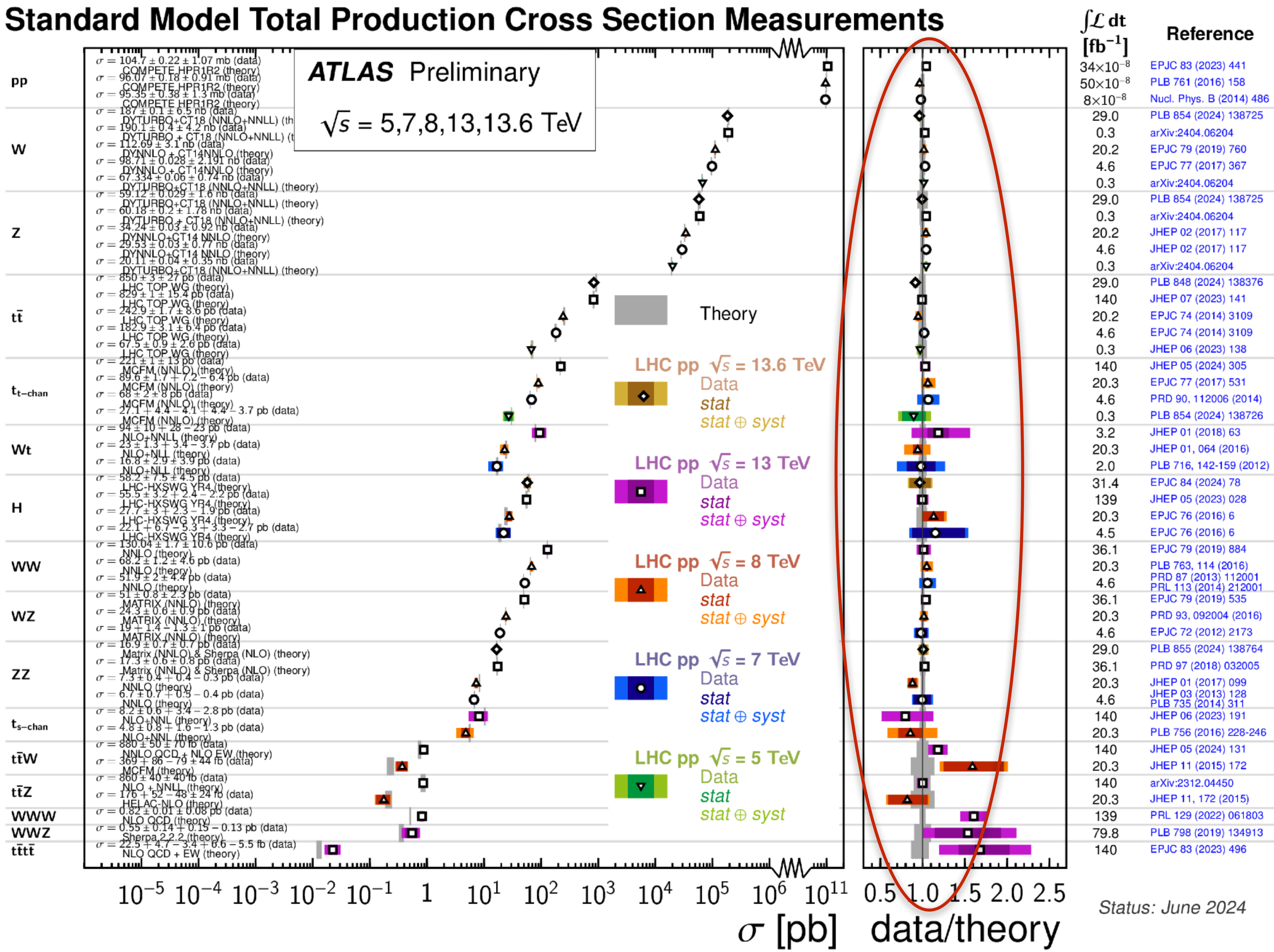
Work in collaboration with M. Reinartz and M. Worek

Based on arXiv:2605.11747 [hep-ph]

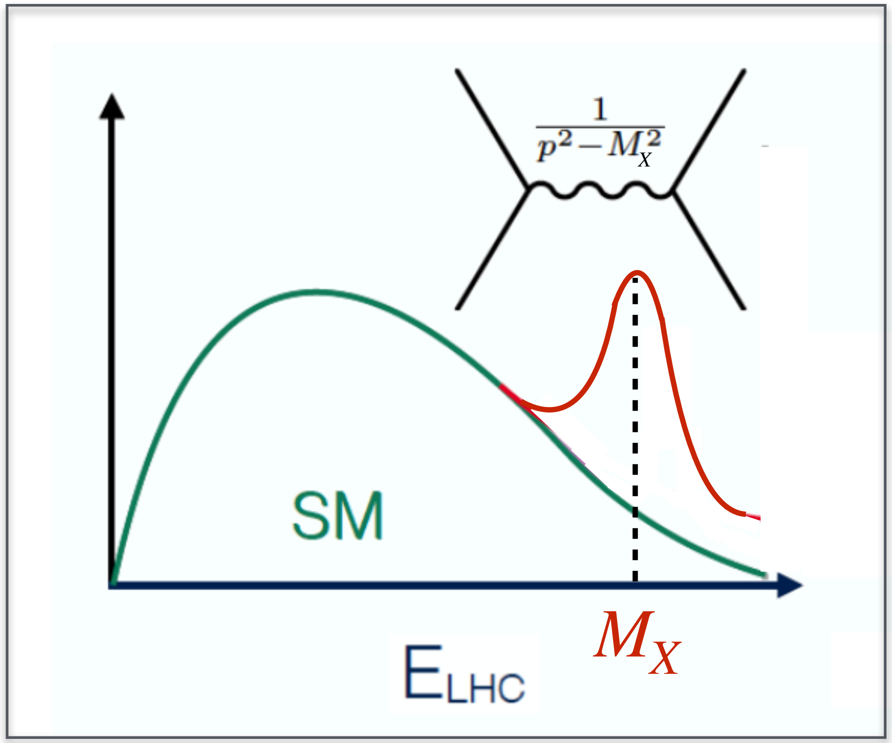
Standard Model: where do we stand?

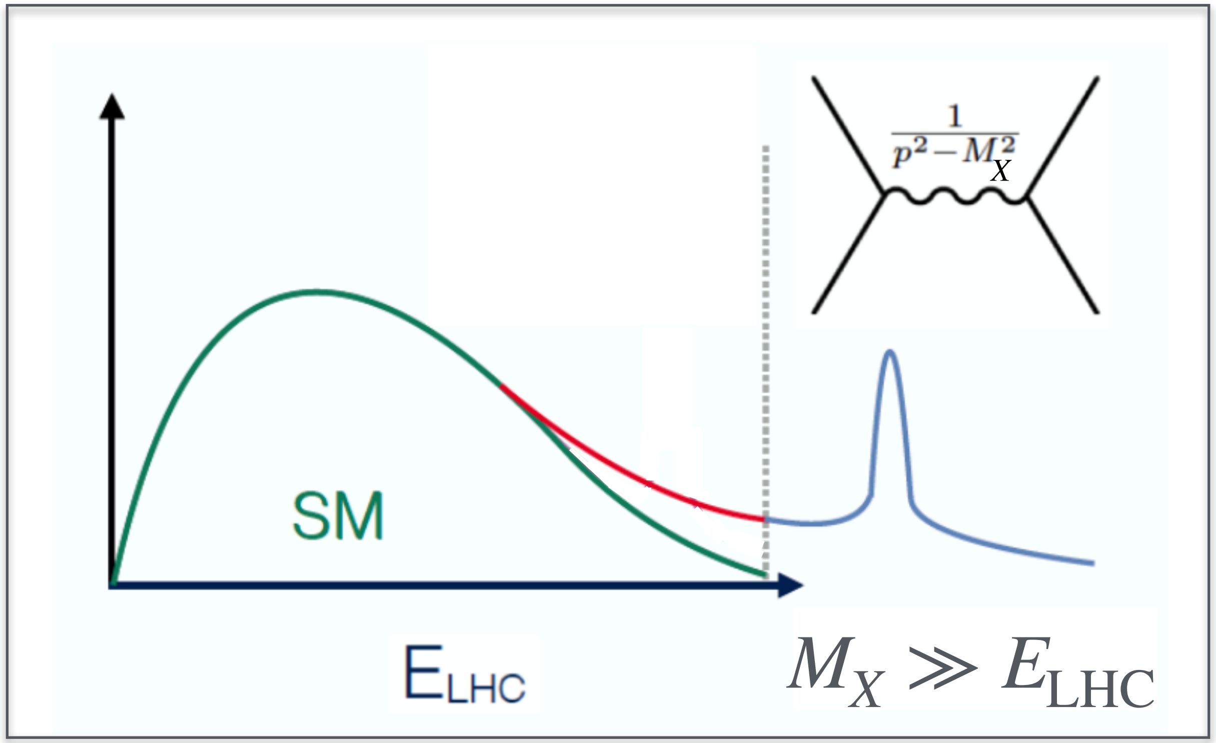
https://atlas.web.cern.ch/Atlas/GROUPS/PHYSICS/PUBNOTES/ATL-PHYS-PUB-2024-011



Standard Model: where do we stand?

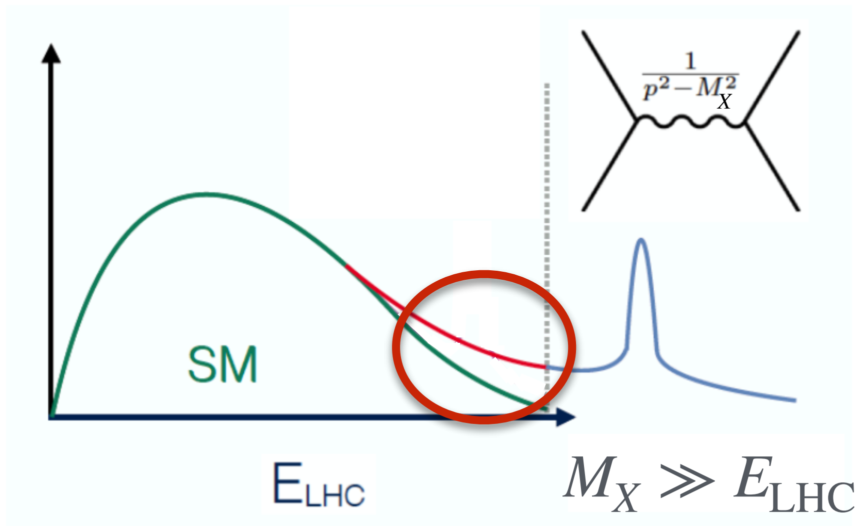
- The SM is in quite good shape!
- New Physics required, but no clear indication of scale
- If new particles exist, either they interact *too weakly* to show up as clear peaks in invariant mass distributions, or they are *too heavy* to be directly produced at the LHC



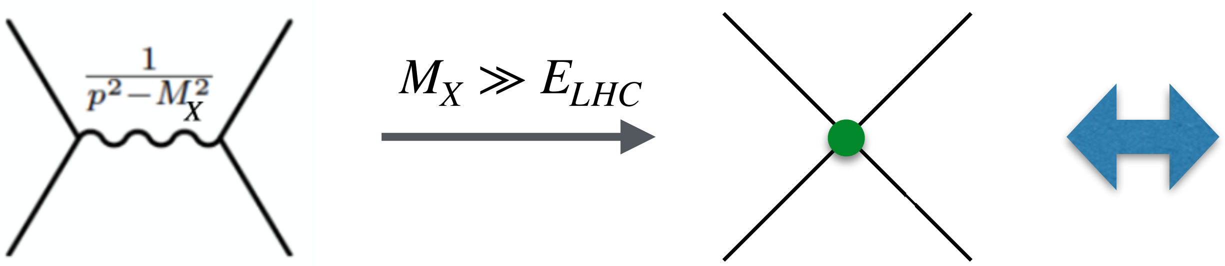


Heavy States at Low Energies

- If the energy scale of the new heavy state is *beyond* the LHC reach, only indirect effects can be detected (→ small enhancements in tails)



- These effects can be described in terms of effective interactions (→ "integrating out" heavy d.o.f.)



$$\frac{C}{M_X^2}\mathcal{O} + \cdots \longrightarrow$$

Effective Lagrangian operator

- If the underlying theory is *known*, C/M_X^2 can be related to the fundamental parameters of the theory

- If the underlying theory is *unknown*, C/M_X^2 can be fitted from experimental data, helping narrowing down candidate fundamental theories

SMEFT in a nutshell

- **S**tandard **M**odel **E**ffective **F**ield **T**heory Lagrangian:

Wilson coefficient

effective operator

$$\mathscr{L}_{\mathrm{SMEFT}} \equiv \mathscr{L}_{\mathrm{SM}} + \underbrace{\sum_i \frac{C_i^{(6)}}{\Lambda^2} \mathcal{O}_i^{(6)}}_{\text{dimension-6 op.}} + \underbrace{\sum_i \frac{C_i^{(8)}}{\Lambda^4} \mathcal{O}_i^{(8)}}_{\text{dimension-8 op.}} + \cdots$$

New Physics scale

- Formal expansion in the (unknown) scale of New Physics → $1/\Lambda^2$
- Order-by-order in the $1/\Lambda^2$ expansion:
  - A *finite* basis of independent operators $\mathcal{O}_i^{(\cdot)}$ can be identified (e.g. Warsaw basis)
  - *higher-order corrections* (QCD, EW) can be computed

↪ Unified framework for model-independent parametrisation of New Physics

SMEFT in Top Quark sector: modelling aspects

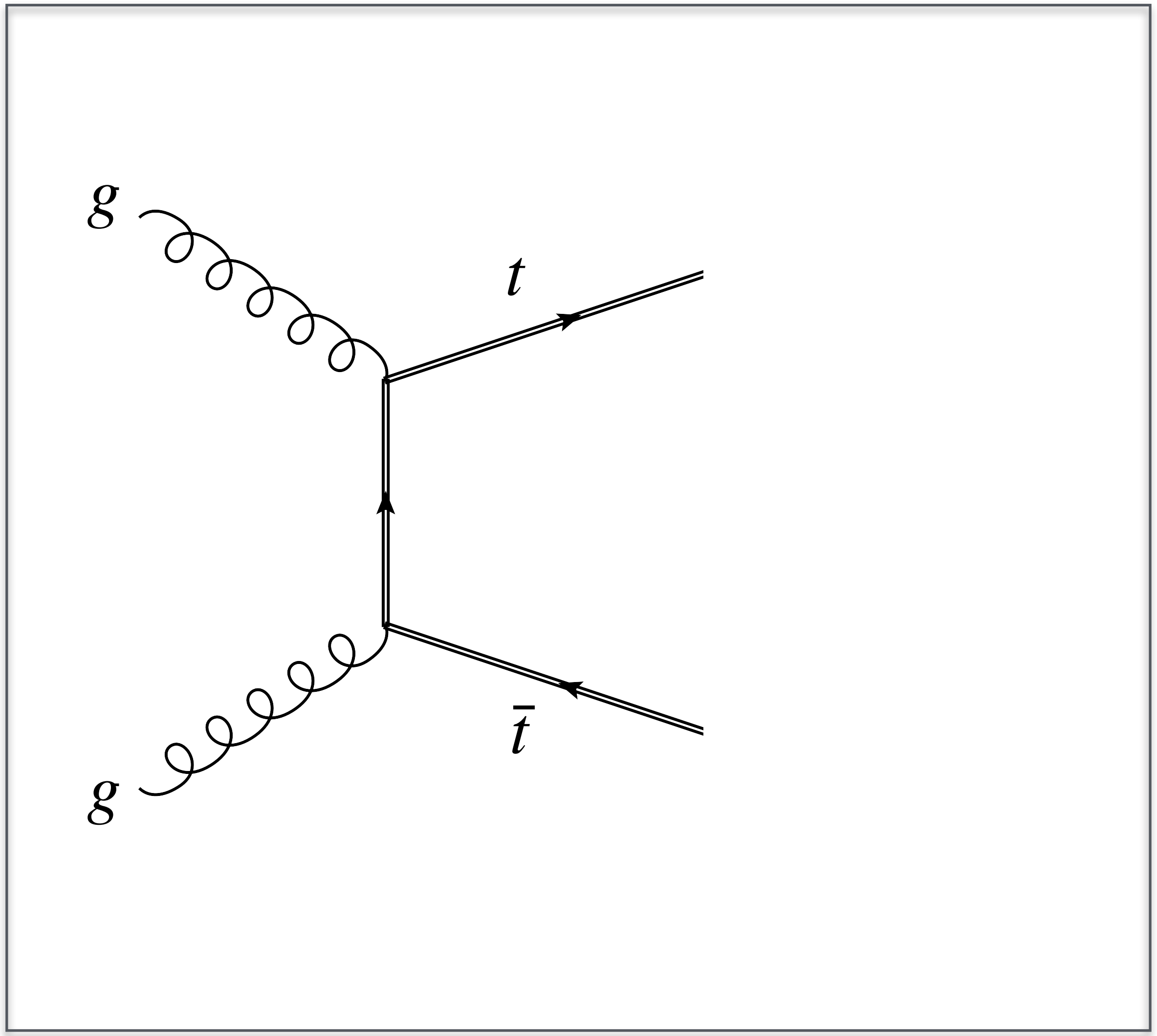
- The Top Quark sector is an interesting place to study SMEFT: many BSM models will modify this sector first

$$m_t \sim v = (G_F\sqrt{2})^{-1}$$
$$y_t = \sqrt{2}m_t/v \approx 1$$

- The quality of SMEFT interpretations in the Top Quark sector depends also on how accurate is the modelling of the processes at hand

- Simplest example: $pp \to t\bar{t}$

  - "*Stable*" ($\to$ fully inclusive predictions)



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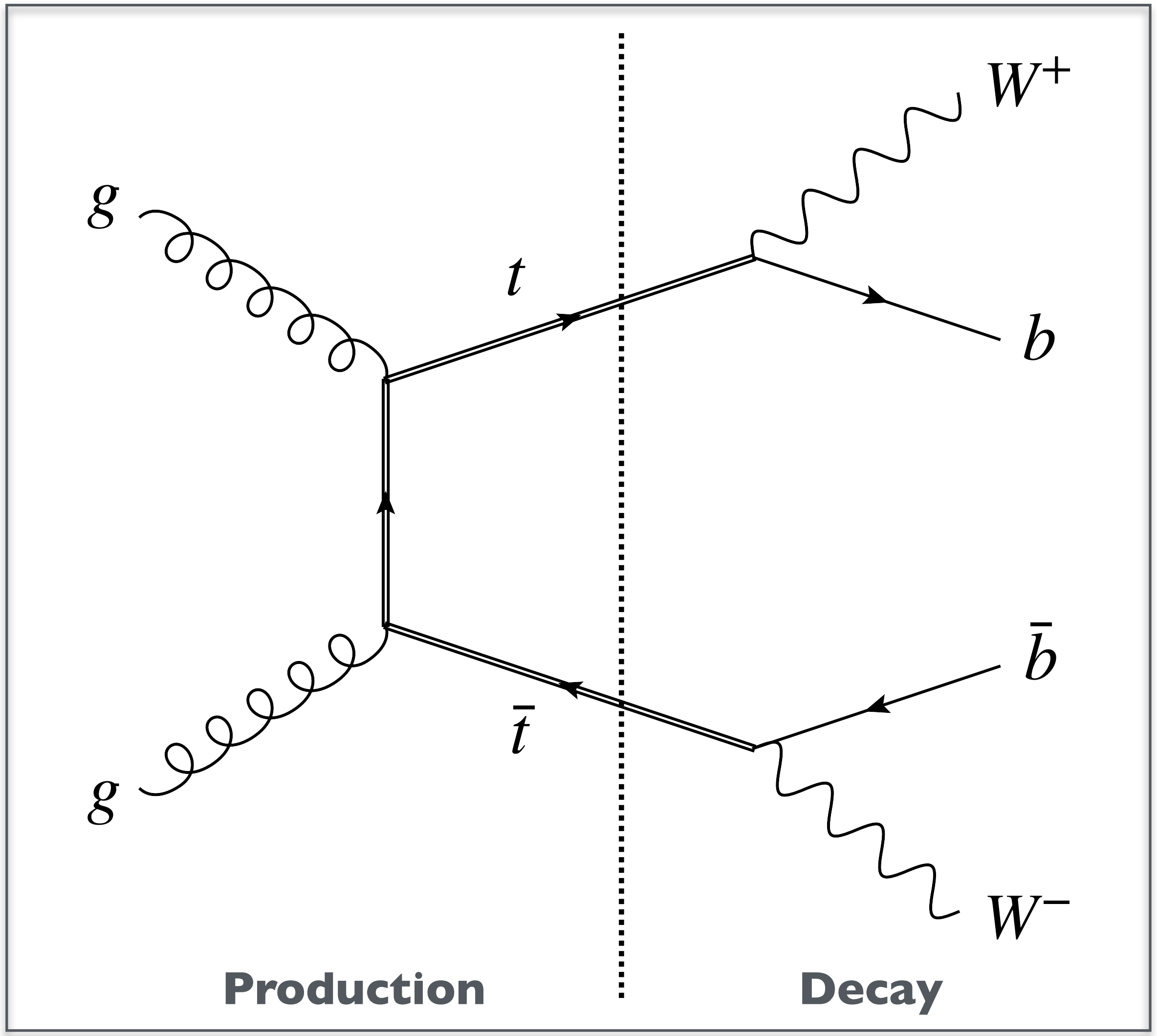
  - *"Production × Decay"* (→ **fiducial cuts**)

$$\boxed{\frac{1}{(p_t^2-m_t^2)^2+m_t^2\Gamma_t^2} \overset{\Gamma_t\to 0}{\sim} \frac{\pi}{m_t\Gamma_t}\,\delta(p_t^2-m^2)+\mathcal{O}\left(\frac{\Gamma_t}{m_t}\right)}$$

Narrow Width Approximation



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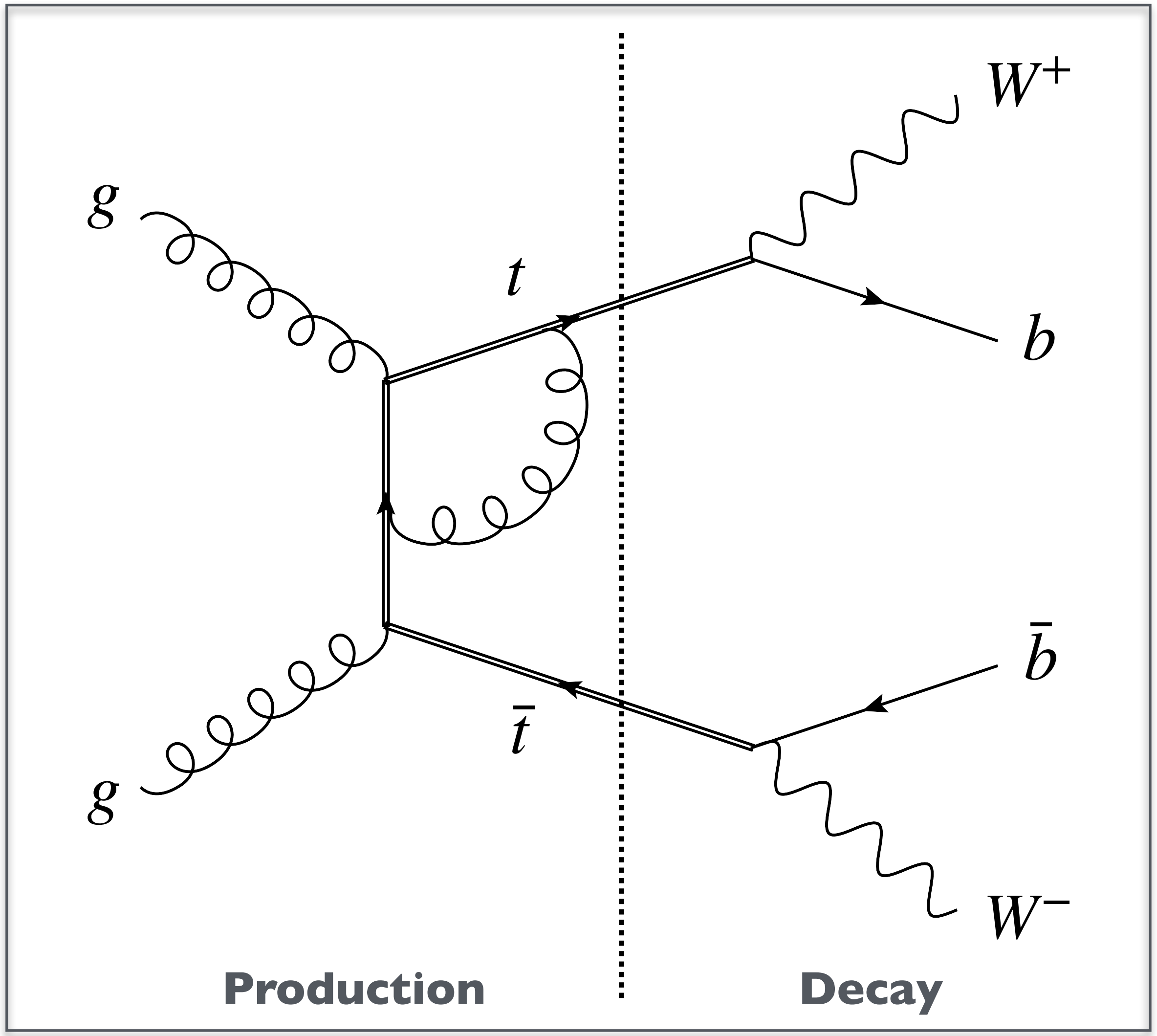

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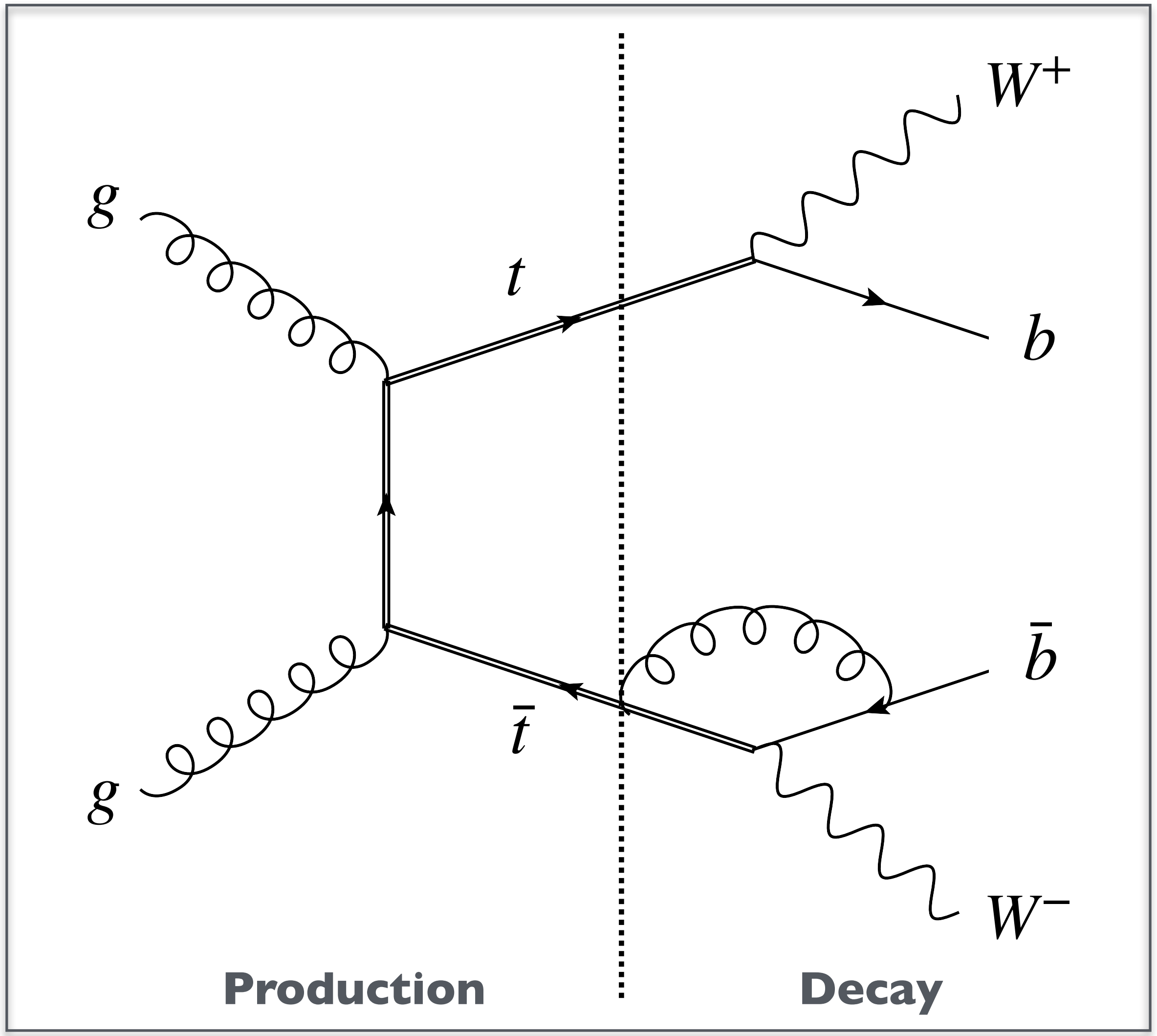

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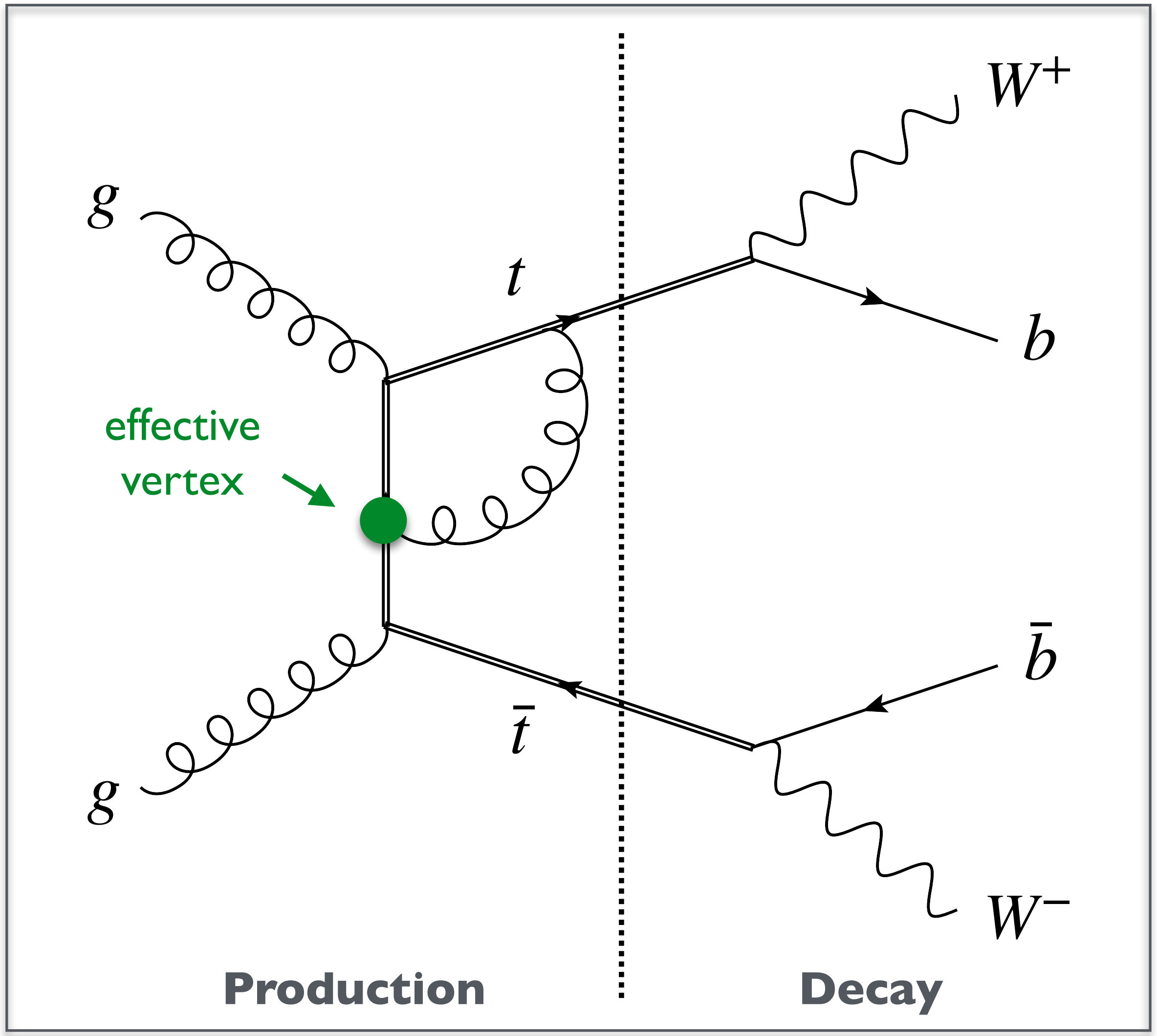

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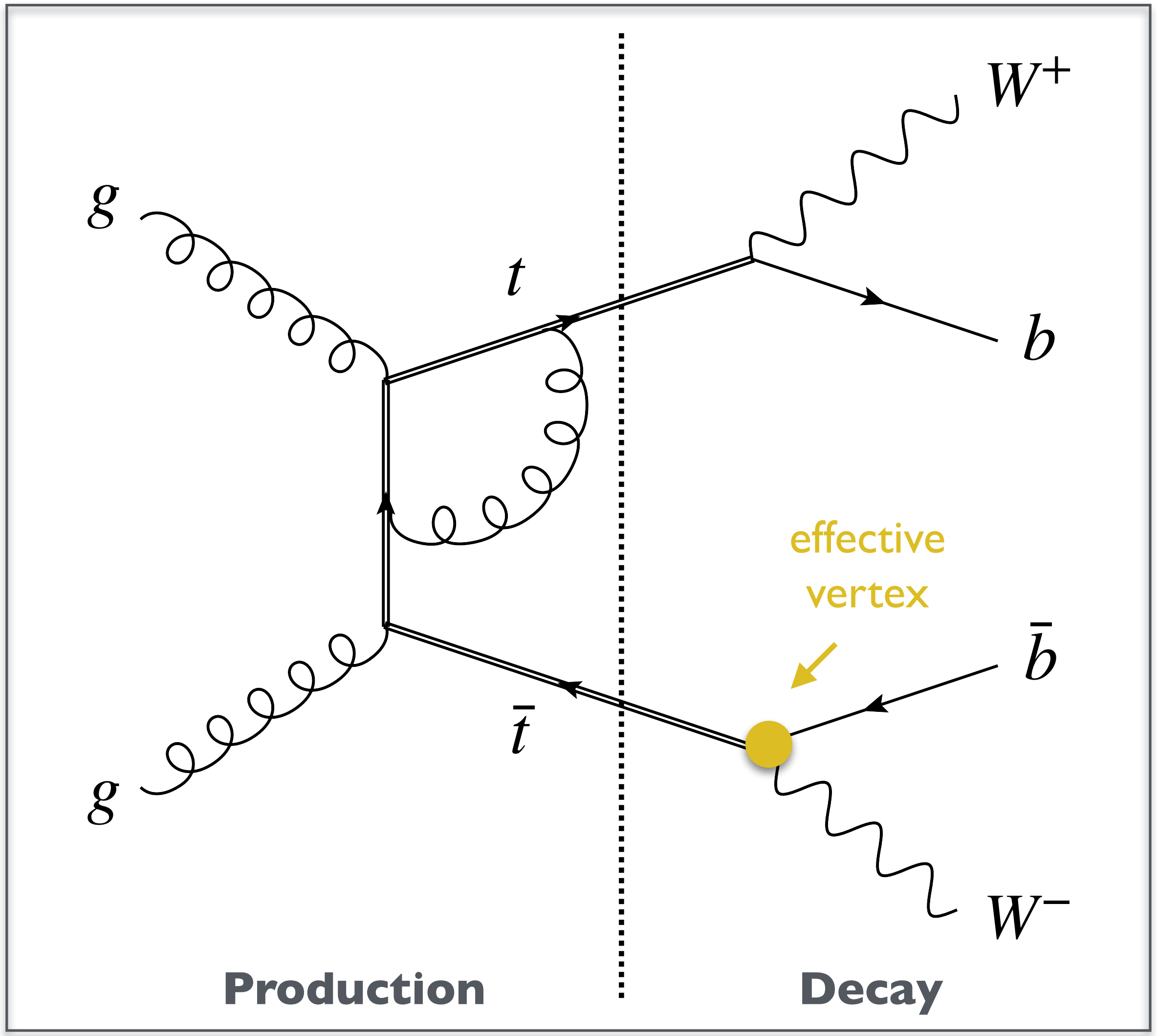

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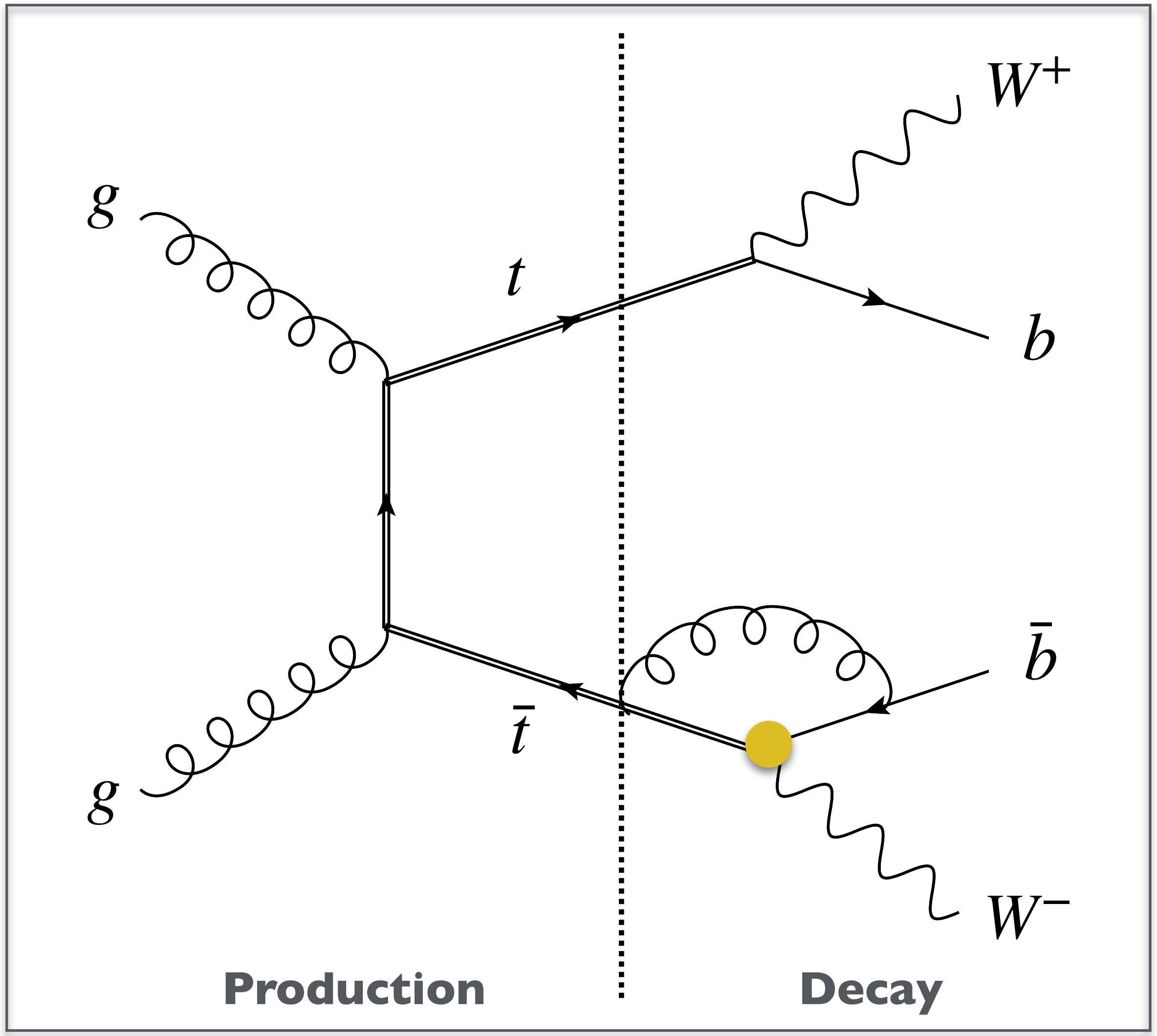

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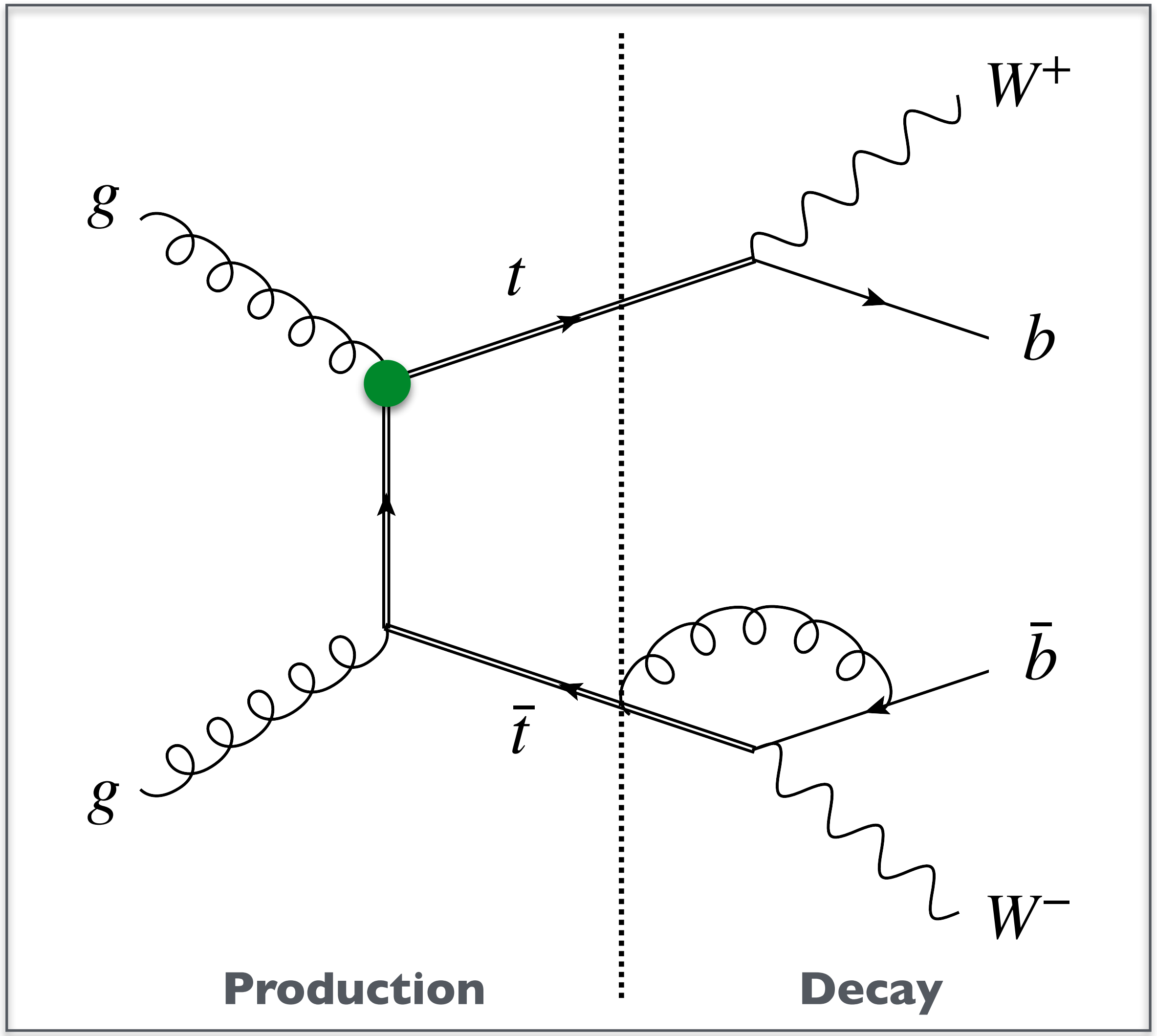
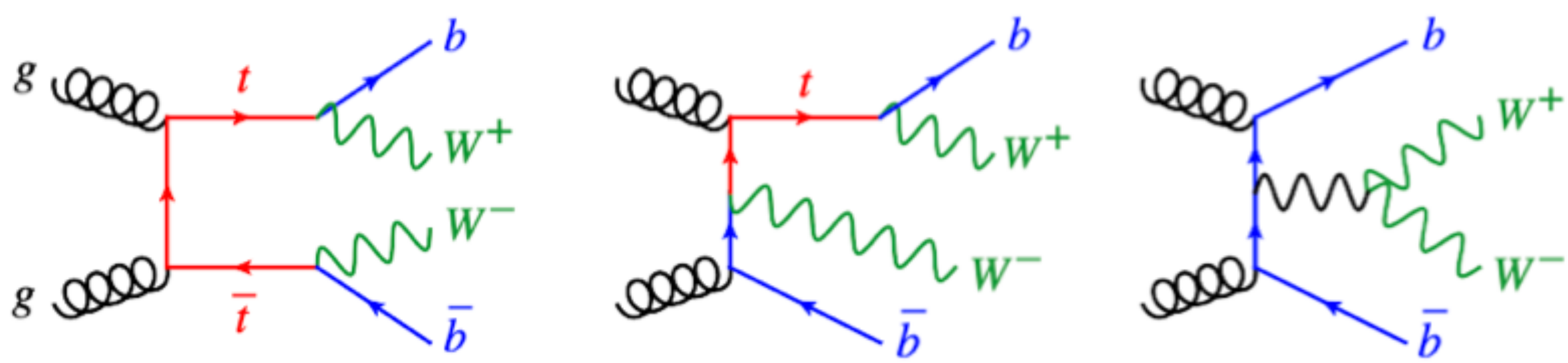


- Beyond NWA: full off-shell calculation

"Off-shell"



"Double resonant" "Single Resonant" "Non Resonant"

" $t\bar{t}$ " " single-top "

"Off-shell" = DR + SR + NR + interferences

Off-shell effects are suppressed by powers of $\Gamma_t/m_t = \mathcal{O}(1\%)$ for *sufficiently inclusive* observables $\rightarrow$ not always true differentially

$\Gamma_t/m_t \approx 0.008 \qquad \Gamma_W/m_W \approx 0.026$

SMEFT in Top Quark sector: state of the art

- Over the past decade, significant progress in calculations SMEFT for Top sector
  - $pp \to t\bar{t}$
  - t-channel single-top
  - $pp \to t\bar{t} + X \quad (X = \gamma, Z, H, t\bar{t})$

  dimension-6 operators, partly at NLO QCD

  [Maltoni, Vryonidou, Zhang, Laenen, Neumann, Sullivan, Hartland, Nocera, Brivio, Plein, Degrande, Rosenfeld…]

- Feynman rules [Dedes *et al.* '17, '23; Brivio *et al.* '17, *Degrande et al.* '20]

- RG evolution and operator mixing [Jenkins *et al.* '13; *Aoude et al.* '22; *Di Noi et al.* '22, '25, Celis *et al.* '17; *Aebisher et al.* '18; …]

- Public models in ***U****niversal* ***F****eynman* ***O****utput format* [Degrande *et al.* '11, '23]

  SMEFTSIM [Brivio *et al.* '17]

  SMEFT@NLO [*Degrande et al.* '20]

- Public Monte Carlo codes (@ NLO QCD)

  Madgraph5_aMC@NLO [Alwall *et al.* '14]

  GoSam3.0 [Braun *et al.* '26]

SMEFT in Top Quark sector: state of the art

- So far, the main work has been done for *stable* top quarks, or by considering only top decays [Boughezal *et al.* '19]

- Beyond state-of-the-art:
  - interplay between SMEFT operators and NLO QCD corrections in top-quark Production and Decay ME's
  - impact of fiducial-level cuts on cross section predictions in SMEFT

- In this work we take the first steps towards simultaneously accounting for SMEFT in the production and top-quark decays for $pp \to t\bar{t}H + X$ at NLO in QCD
  - using the NWA, study the process

$$pp \to t\bar{t}H \to W^+W^-b\bar{b}H \to e^+\nu_e\mu^-\nu_\mu b\bar{b}H$$

  - focus on a minimal, realistic set of effective operators
  - assess dominant theoretical uncertainties

$pp \to t\bar{t}H$: effective operators & vertices

- Effective *dimension-6* operators considered in our study:

$\mathcal{O}_{t\phi} = \left(\phi^\dagger\phi - \frac{v^2}{2}\right)\bar{Q}t\tilde{\phi} + \text{h.c.}$	$\mathcal{O}_{tG} = ig_s\,(\bar{Q}\,\sigma^{\mu\nu}\,T_a\,t)\,\tilde{\phi}\,G^a_{\mu\nu} + \text{h.c.}$
$\mathcal{O}_{\phi G} = \left(\phi^\dagger\phi - \frac{v^2}{2}\right)G_a^{\mu\nu}G^a_{\mu\nu}$	$\mathcal{O}_{tW} = i\,(\bar{Q}\,\sigma^{\mu\nu}\,\sigma_I\,t)\,\tilde{\phi}\,W^I_{\mu\nu} + \text{h.c.}$

where

$\phi \equiv$ Higgs doublet $\quad \tilde{\phi} \equiv i\sigma^2\phi^\dagger \quad v \equiv$ Higgs VEV

$Q \equiv \begin{pmatrix} t_L \\ b_L \end{pmatrix} \quad t \equiv t_R$

$G^a_{\mu\nu} =$ gluon's field-strength tensor

$\sigma^{\mu\nu} \equiv \frac{1}{2}[\gamma^\mu, \gamma^\nu] \quad \sigma_I \equiv$ Pauli matrices

$pp \to t\bar{t}H$: effective operators & vertices

- Effective vertices induced by these operators, relevant for $pp \to t\bar{t}H$ (dilepton)

$\mathcal{O}_{t\phi} = \left(\phi^\dagger\phi - \frac{v^2}{2}\right)\bar{Q}t\tilde{\phi}$ + h.c.	$\mathcal{O}_{tG} = ig_s\,(\bar{Q}\,\sigma^{\mu\nu}\,T_a\,t)\,\tilde{\phi}\,G^a_{\mu\nu}$ + h.c.
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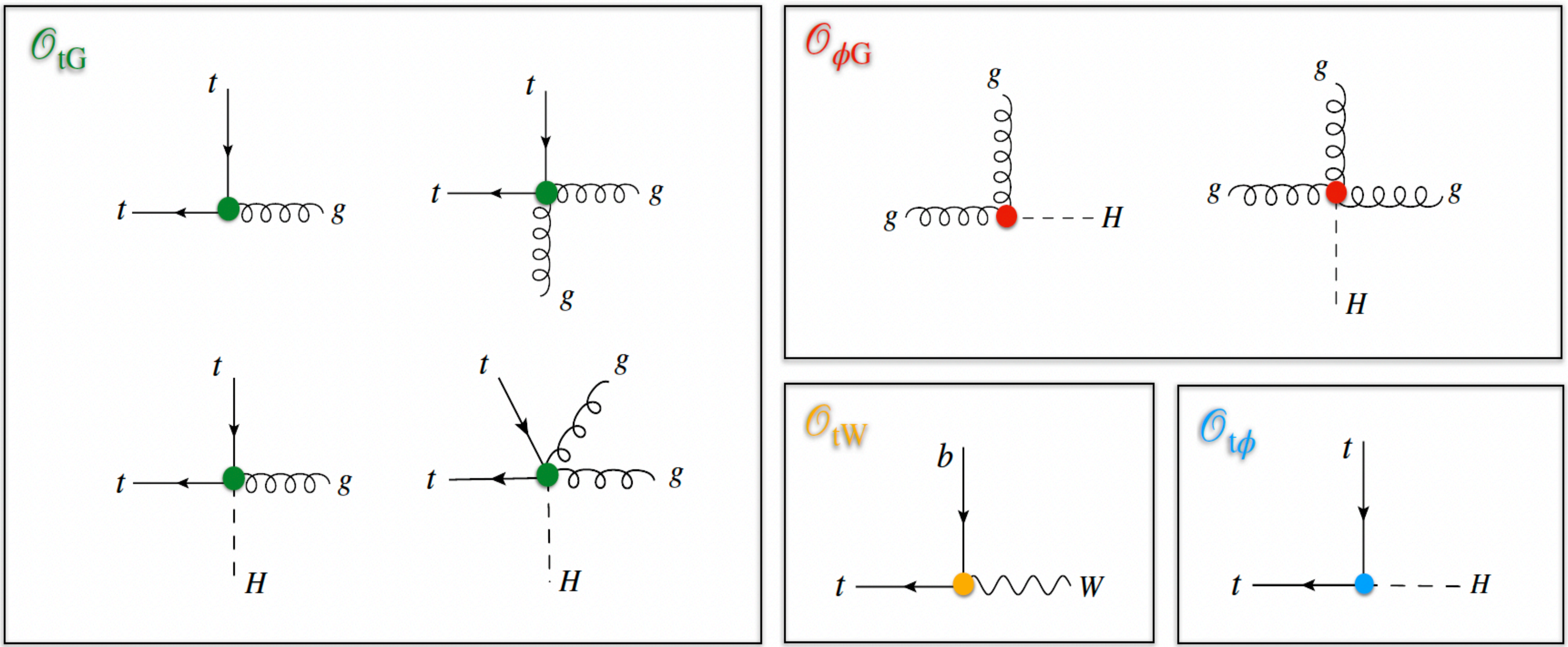

$pp \to t\bar{t}H$: effective operators & vertices

- RG evolution from Λ to μ_{EFT} leads to mixing of operator coefficients

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$$C_i \equiv (C_{t\phi}, C_{\phi G}, C_{tG}, C_{tW})$$

$$\frac{dC_i}{d\log(\mu_{EFT})} = \gamma_{ij}\,C_j$$

$$\gamma_{ij} = \sum_{k=1}^{\infty}\left(\frac{\alpha_s}{4\pi}\right)\gamma_{ij}^{\mathrm{QCD,k}}$$

$$\gamma_{ij}^{\mathrm{QCD,1}} = \frac{1}{3}\begin{pmatrix} -24 & 96\,y_t & 96\,y_t^2 & 0 \\ 0 & -6\,\beta^{(6)} & 12\,y_t & 0 \\ 0 & 0 & 4 & 0 \\ 0 & 0 & 8\,g & 8 \end{pmatrix}$$

[Aoude *et al.*, *JHEP* 09 (2023) 191]

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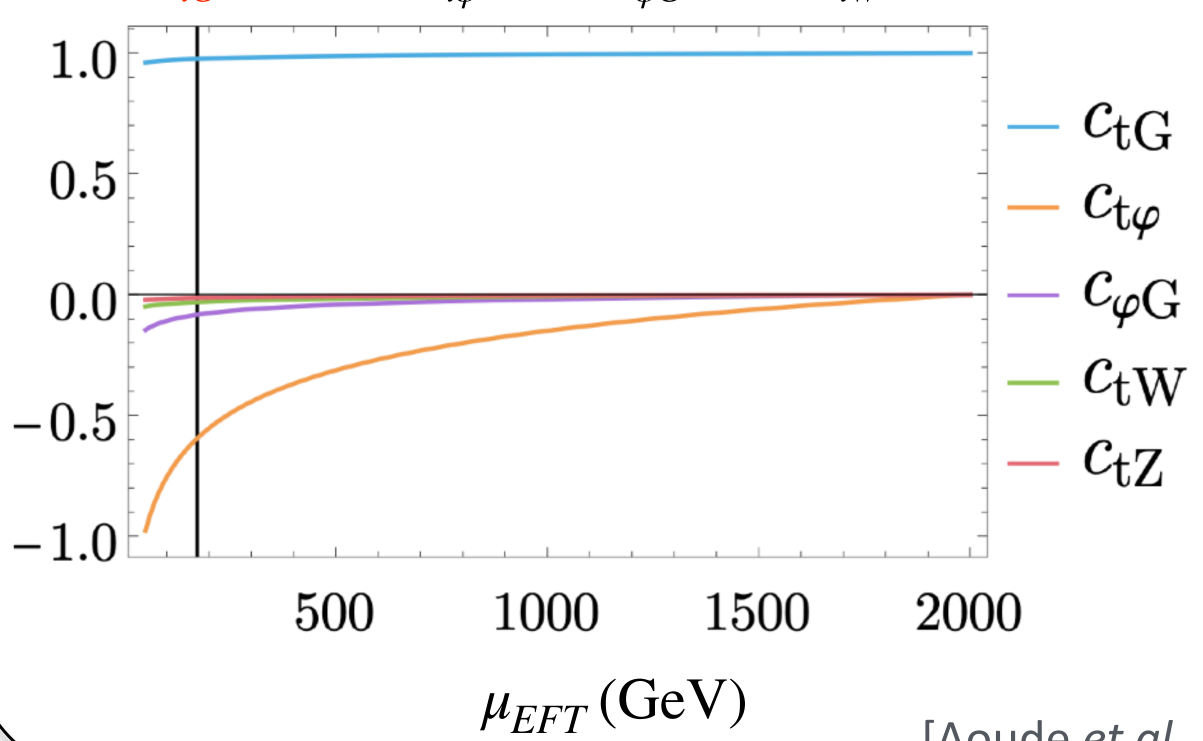
Examples ($\Lambda = 2000\,\mathrm{GeV}$)

$C_{tG}(\Lambda) = 1$; $C_{t\phi}(\Lambda) = C_{\phi G}(\Lambda) = C_{tW}(\Lambda) = 0$



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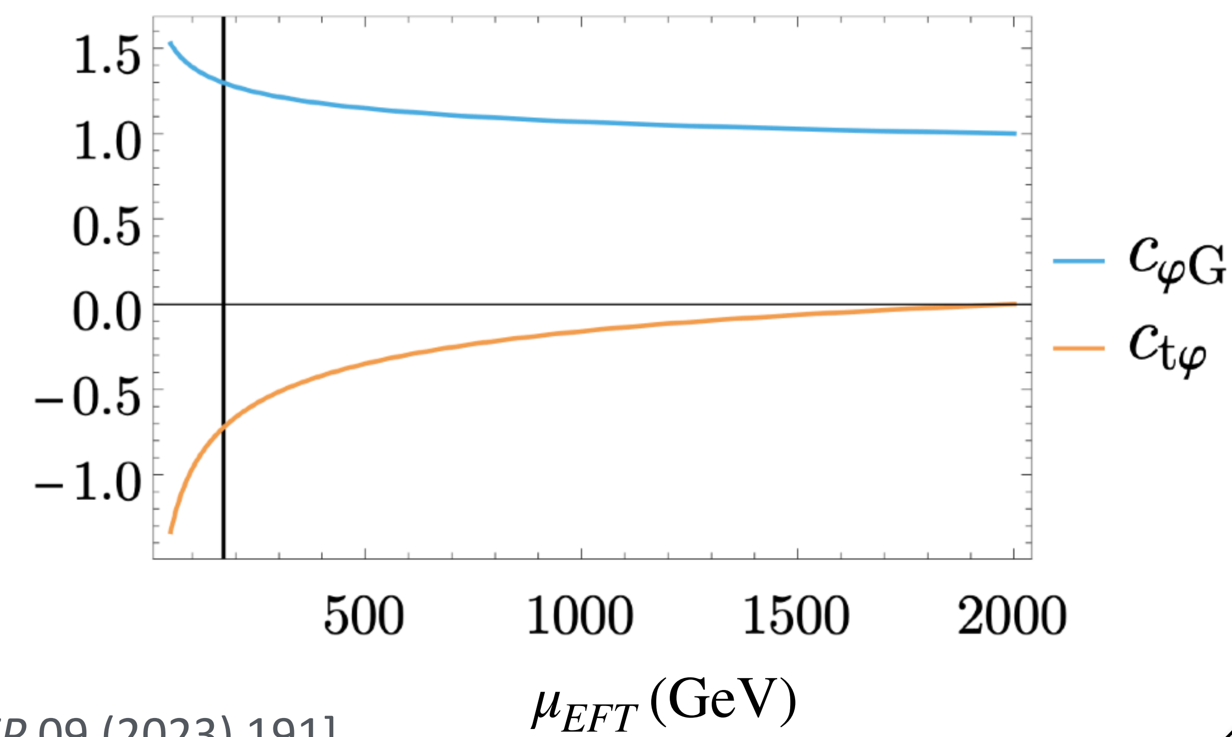
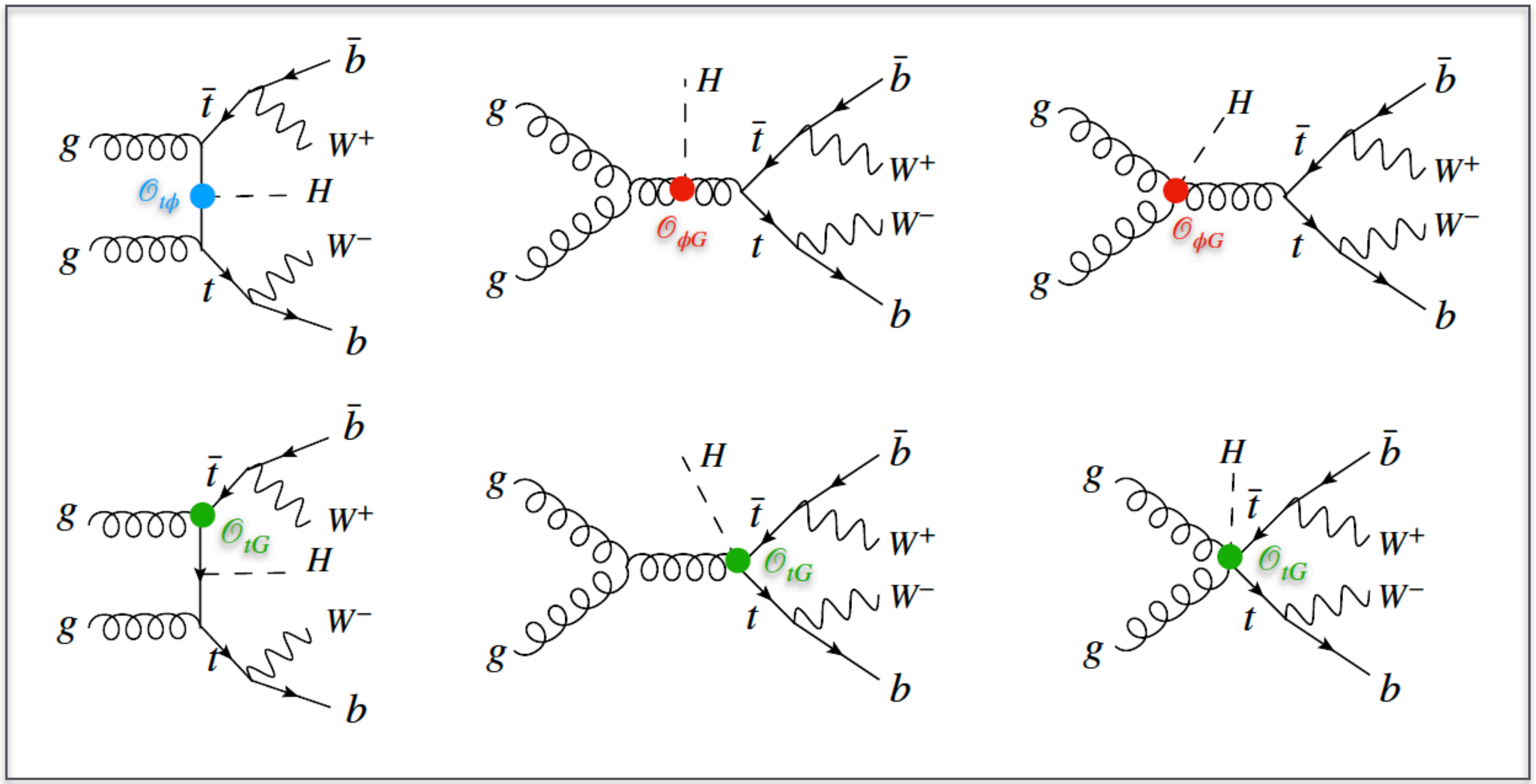


[Aoude *et al.*, *JHEP* 09 (2023) 191]

$pp \to t\bar{t}H$: SMEFT in Production and Decays

- Representative examples of contributions from $\mathcal{O}_{t\phi}$, $\mathcal{O}_{\phi G}$, $\mathcal{O}_{tG}$, $\mathcal{O}_{tW}$ entering $pp \to t\bar{t}H \to b\bar{b}W^+W^-H$

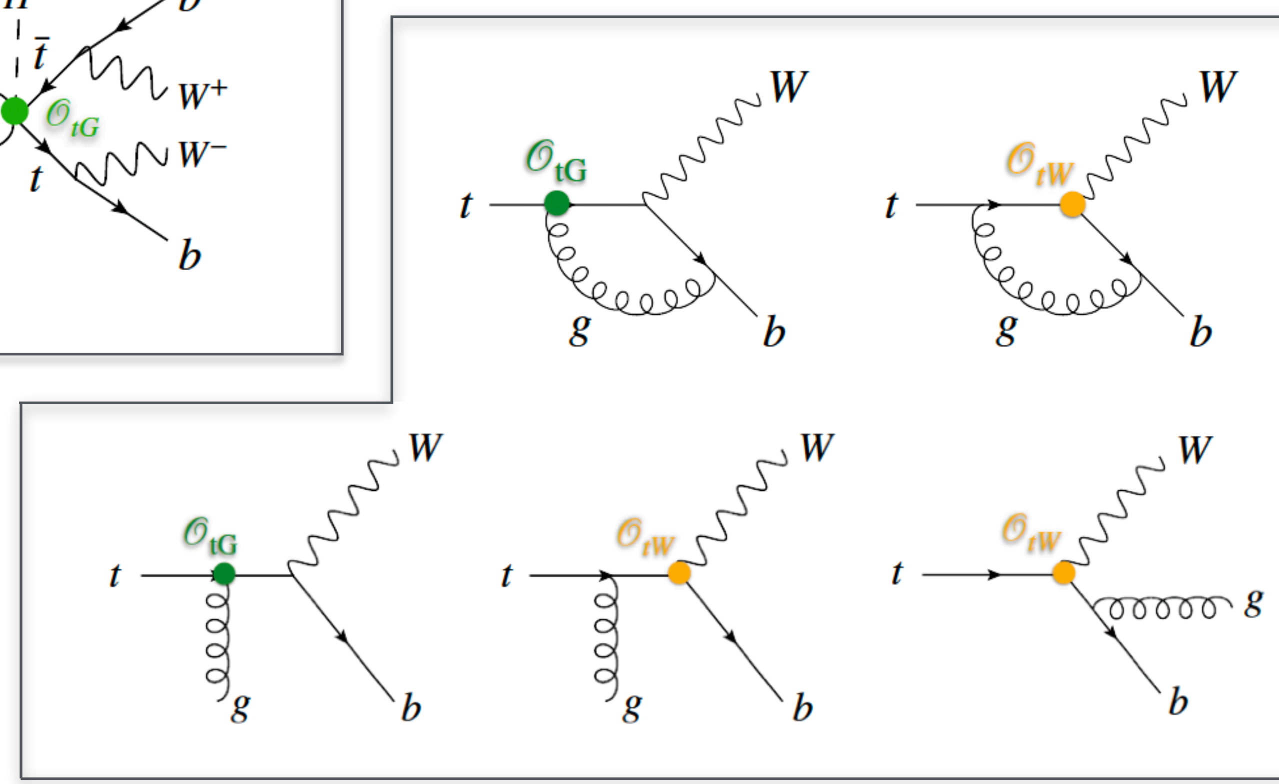


at Production

$\mathcal{O}_{t\phi}$ $\mathcal{O}_{\phi G}$ $\mathcal{O}_{tG}$

at Decay

$\mathcal{O}_{tW}$ $\mathcal{O}_{tG}$



At NLO QCD, decays acquire sensitivity to $\mathcal{O}_{tG}$

Computational framework

- We developed a new tool for NLO computations in SMEFT, building upon HELAC-NLO [G.B, Czakon, Garzelli, van Hameren, Kardos, Papadopoulos, Pittau and Worek, '11]

- Goals:

  - *Flexible* in the number of effective operators that can be implemented
  - Handle both NWA and full off-shell calculations within the same framework
  - Consistently take into account contributions of the effective operators and QCD corrections in the Production and Decay part
  - Deliver all partial contributions from individual SMEFT operators in a *single* run
  - Store and reuse the obtained results to provide theoretical predictions for different scale (μ_R, μ_F, μ_{EFT}) settings, different PDF sets, different kinematical cuts…

Computational framework

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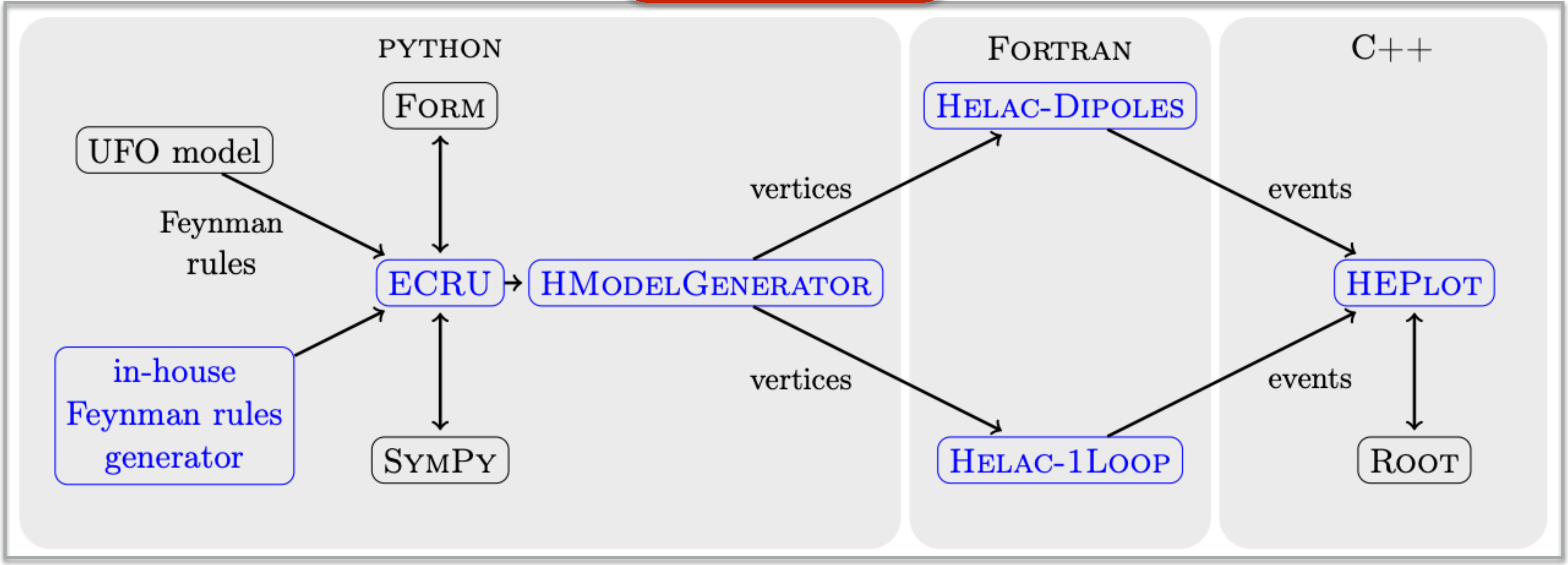
G.B, Reinartz and Worek, [arXiv:2605.11747 [hep-ph]]

HELAC-SMEFT



For our study we employ the UFO model SMEFT@NLO

[C. Degrande *et al.*, *Phys. Rev. D 103, 096024 (2021)*]

Anatomy of SMEFT cross sections

- The cross section can be parametrised as follows:

$$\sigma(\mu_R, \mu_F, \mu_{EFT}) \;=\; \sigma_{\rm SM}(\mu_R, \mu_F) \;+\; \underbrace{\sum_i \Sigma_i^{\rm SMEFT}(\mu_R, \mu_F, \mu_{EFT})}_{\textit{Linear}\text{ SMEFT contributions}} \;+\; \underbrace{\sum_{j\geq i} \Sigma_{ij}^{\rm SMEFT}(\mu_R, \mu_F, \mu_{EFT})}_{\textit{Quadratic}\text{ SMEFT contributions}}$$

[$\mu_R =$ *renormalisation* scale $\mu_F =$ *factorisation* scale $\mu_{EFT} =$ *effective* scale]

- When μ_{EFT} is *fixed*, operator coefficients can be factored out:

$$\Sigma_i^{\rm SMEFT}(\mu_R, \mu_F, \mu_{EFT}) \;=\; \frac{1\ {\rm TeV}^2}{\Lambda^2}\, C_i(\mu_{EFT})\, \sigma_i(\mu_R, \mu_F, \mu_{EFT})$$

$$\Sigma_{ij}^{\rm SMEFT}(\mu_R, \mu_F, \mu_{EFT}) \;=\; \frac{1\ {\rm TeV}^4}{\Lambda^4}\, C_i(\mu_{EFT})\, C_j(\mu_{EFT})\, \sigma_{ij}(\mu_R, \mu_F, \mu_{EFT})$$

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$$\Sigma_{ij}^{\rm SMEFT}(\mu_R,\mu_F,\mu_{EFT}) = \frac{1\ \text{TeV}^4}{\Lambda^4} C_i(\mu_{EFT})\, C_j(\mu_{EFT})\, \sigma_{ij}(\mu_R,\mu_F,\mu_{EFT}) \quad \rightarrow \sigma_{t\phi,t\phi}, \sigma_{t\phi,\phi G}, \ldots$$

$t\bar{t}H$ (dilepton): integrated cross sections

G.B, Reinartz and Worek, arXiv:2605.11747 [hep-ph]

$pp \to e^+\nu_e\,\mu^-\bar{\nu}_\mu\,b\bar{b}\,H + X$ (NWA) $\sqrt{s} = 13.6$ TeV

		$\sigma^{\rm LO}$[fb]	$\sigma^{\rm LO}/\sigma^{\rm LO}_{\rm SM}$	$\sigma^{\rm NLO}$[fb]	$\sigma^{\rm NLO}/\sigma^{\rm NLO}_{\rm SM}$	$\mathcal{K}$
	σ_{SM}	$2.3166^{+0.7068\,+0.0000}_{-0.5044\,-0.0000}$	$1.000^{+0.000\,+0.000}_{-0.000\,-0.000}$	$2.7680^{+0.0560\,+0.0000}_{-0.1898\,-0.0000}$	$1.000^{+0.000\,+0.000}_{-0.000\,-0.000}$	1.19
Linear	$\sigma_{t\phi}$	$-0.2835^{+0.0617\,+0.0122}_{-0.0865\,-0.0139}$	$-0.122^{+0.000\,+0.005}_{-0.000\,-0.006}$	$-0.3578^{+0.0287\,+0.0033}_{-0.0117\,-0.0045}$	$-0.129^{+0.002\,+0.001}_{-0.003\,-0.002}$	1.26
	$\sigma_{\phi G}$	$1.6262^{+0.5137\,+0.2000}_{-0.3638\,-0.1668}$	$0.702^{+0.006\,+0.086}_{-0.005\,-0.072}$	$2.6114^{+0.3238\,+0.1102}_{-0.3337\,-0.0919}$	$0.943^{+0.107\,+0.040}_{-0.060\,-0.033}$	1.61
	σ_{tG}	$2.4217^{+0.7568\,+0.0105}_{-0.5374\,-0.0131}$	$1.045^{+0.006\,+0.005}_{-0.006\,-0.006}$	$2.8196^{+0.0454\,+0.0130}_{-0.1757\,-0.0153}$	$1.019^{+0.007\,+0.005}_{-0.017\,-0.006}$	1.16
	σ_{tW}	$0.7238^{+0.2214\,+0.0107}_{-0.1579\,-0.0115}$	$0.312^{+0.000\,+0.005}_{-0.000\,-0.005}$	$0.8669^{+0.0178\,+0.0019}_{-0.0600\,-0.0033}$	$0.313^{+0.000\,+0.001}_{-0.000\,-0.001}$	1.20
Quadratic	$\sigma_{t\phi,t\phi}$	$0.0087^{+0.0026\,+0.0009}_{-0.0019\,-0.0007}$	$0.004^{+0.000\,+0.000}_{-0.000\,-0.000}$	$0.0115^{+0.0006\,+0.0003}_{-0.0010\,-0.0003}$	$0.004^{+0.000\,+0.000}_{-0.000\,-0.000}$	1.33
	$\sigma_{t\phi,\phi G}$	$-0.0995^{+0.0223\,+0.0140}_{-0.0314\,-0.0177}$	$-0.043^{+0.000\,+0.006}_{-0.000\,-0.008}$	$-0.1663^{+0.0223\,+0.0095}_{-0.0228\,-0.0110}$	$-0.060^{+0.004\,+0.003}_{-0.008\,-0.004}$	1.67
	$\sigma_{t\phi,tG}$	$-0.1482^{+0.0329\,+0.0058}_{-0.0463\,-0.0064}$	$-0.064^{+0.000\,+0.002}_{-0.000\,-0.003}$	$-0.1822^{+0.0136\,+0.0007}_{-0.0037\,-0.0011}$	$-0.066^{+0.000\,+0.000}_{-0.001\,-0.000}$	1.23
	$\sigma_{t\phi,tW}$	$-0.0443^{+0.0097\,+0.0013}_{-0.0135\,-0.0014}$	$-0.019^{+0.000\,+0.001}_{-0.000\,-0.001}$	$-0.0559^{+0.0045\,+0.0003}_{-0.0018\,-0.0005}$	$-0.020^{+0.000\,+0.000}_{-0.000\,-0.000}$	1.26
	$\sigma_{\phi G,\phi G}$	$0.8178^{+0.2987\,+0.1718}_{-0.2032\,-0.1314}$	$0.353^{+0.016\,+0.074}_{-0.014\,-0.057}$	$1.6003^{+0.2802\,+0.1528}_{-0.2598\,-0.1286}$	$0.578^{+0.095\,+0.055}_{-0.058\,-0.046}$	1.96
	$\sigma_{\phi G,tG}$	$1.5954^{+0.5561\,+0.1296}_{-0.3835\,-0.1132}$	$0.689^{+0.023\,+0.056}_{-0.020\,-0.049}$	$2.5519^{+0.2729\,+0.0593}_{-0.3254\,-0.0488}$	$0.922^{+0.089\,+0.021}_{-0.058\,-0.018}$	1.60
	$\sigma_{\phi G,tW}$	$0.2548^{+0.0807\,+0.0268}_{-0.0571\,-0.0227}$	$0.110^{+0.001\,+0.012}_{-0.001\,-0.010}$	$0.4091^{+0.0508\,+0.0146}_{-0.0524\,-0.0120}$	$0.148^{+0.017\,+0.005}_{-0.009\,-0.004}$	1.61
	$\sigma_{tG,tG}$	$3.4828^{+1.2967\,+0.0635}_{-0.8776\,-0.0700}$	$1.503^{+0.077\,+0.027}_{-0.066\,-0.030}$	$4.3143^{+0.0377\,+0.0225}_{-0.2985\,-0.0320}$	$1.559^{+0.009\,+0.008}_{-0.071\,-0.012}$	1.24
	$\sigma_{tG,tW}$	$0.3795^{+0.1189\,+0.0076}_{-0.0843\,-0.0084}$	$0.164^{+0.001\,+0.003}_{-0.001\,-0.004}$	$0.4412^{+0.0071\,+0.0029}_{-0.0274\,-0.0040}$	$0.159^{+0.001\,+0.001}_{-0.003\,-0.001}$	1.16
	$\sigma_{tW,tW}$	$0.0754^{+0.0231\,+0.0022}_{-0.0165\,-0.0024}$	$0.033^{+0.000\,+0.001}_{-0.000\,-0.001}$	$0.0895^{+0.0018\,+0.0004}_{-0.0060\,-0.0007}$	$0.032^{+0.000\,+0.000}_{-0.000\,-0.000}$	1.19

Kinematic cuts:

$p_T(b) > 25$ GeV $\quad |y(b)| < 2.5 \quad \Delta R(bb) > 0.4$

$p_T(\ell) > 25$ GeV $\quad |y(\ell)| < 2.5 \quad \Delta R(\ell\ell) > 0.4$

Scale settings:

$$\mu_R = \mu_F = m_t + \frac{m_H}{2}\,, \quad \mu_{EFT} = m_t$$

$t\bar{t}H$ (dilepton): integrated cross sections

G.B, Reinartz and Worek, [arXiv:2605.11747 [hep-ph]]

$pp \to e^+\nu_e\,\mu^-\bar{\nu}_\mu\, b\bar{b}\, H + X$ (NWA) $\sqrt{s} = 13.6$ TeV

Group		$\sigma^{\rm LO}$[fb]	$\sigma^{\rm LO}/\sigma^{\rm LO}_{\rm SM}$	$\sigma^{\rm NLO}$[fb]	$\sigma^{\rm NLO}/\sigma^{\rm NLO}_{\rm SM}$	$\mathcal{K}$
	σ_{SM}	$2.3166^{+0.7068\,+0.0000}_{-0.5044\,-0.0000}$	$1.000^{+0.000\,+0.000}_{-0.000\,-0.000}$	$2.7680^{+0.0560\,+0.0000}_{-0.1898\,-0.0000}$	$1.000^{+0.000\,+0.000}_{-0.000\,-0.000}$	1.19
Linear	$\sigma_{t\phi}$	$-0.2835^{+0.0617\,+0.0122}_{-0.0865\,-0.0139}$	$-0.122^{+0.000\,+0.005}_{-0.000\,-0.006}$	$-0.3578^{+0.0287\,+0.0033}_{-0.0117\,-0.0045}$	$-0.129^{+0.002\,+0.001}_{-0.003\,-0.002}$	1.26
Linear	$\sigma_{\phi G}$	$1.6262^{+0.5137\,+0.2000}_{-0.3638\,-0.1668}$	$0.702^{+0.006\,+0.086}_{-0.005\,-0.072}$	$2.6114^{+0.3238\,+0.1102}_{-0.3337\,-0.0919}$	$0.943^{+0.107\,+0.040}_{-0.060\,-0.033}$	1.61
Linear	σ_{tG}	$2.4217^{+0.7568\,+0.0105}_{-0.5374\,-0.0131}$	$1.045^{+0.006\,+0.005}_{-0.006\,-0.006}$	$2.8196^{+0.0454\,+0.0130}_{-0.1757\,-0.0153}$	$1.019^{+0.007\,+0.005}_{-0.017\,-0.006}$	1.16
Linear	σ_{tW}	$0.7238^{+0.2214\,+0.0107}_{-0.1579\,-0.0115}$	$0.312^{+0.000\,+0.005}_{-0.000\,-0.005}$	$0.8669^{+0.0178\,+0.0019}_{-0.0600\,-0.0033}$	$0.313^{+0.000\,+0.001}_{-0.000\,-0.001}$	1.20
Quadratic	$\sigma_{t\phi,t\phi}$	$0.0087^{+0.0026\,+0.0009}_{-0.0019\,-0.0007}$	$0.004^{+0.000\,+0.000}_{-0.000\,-0.000}$	$0.0115^{+0.0006\,+0.0003}_{-0.0010\,-0.0003}$	$0.004^{+0.000\,+0.000}_{-0.000\,-0.000}$	1.33
Quadratic	$\sigma_{t\phi,\phi G}$	$-0.0995^{+0.0223\,+0.0140}_{-0.0314\,-0.0177}$	$-0.043^{+0.000\,+0.006}_{-0.000\,-0.008}$	$-0.1663^{+0.0223\,+0.0095}_{-0.0228\,-0.0110}$	$-0.060^{+0.004\,+0.003}_{-0.008\,-0.004}$	1.67
Quadratic	$\sigma_{t\phi,tG}$	$-0.1482^{+0.0329\,+0.0058}_{-0.0463\,-0.0064}$	$-0.064^{+0.000\,+0.002}_{-0.000\,-0.003}$	$-0.1822^{+0.0136\,+0.0007}_{-0.0037\,-0.0011}$	$-0.066^{+0.000\,+0.000}_{-0.001\,-0.000}$	1.23
Quadratic	$\sigma_{t\phi,tW}$	$-0.0443^{+0.0097\,+0.0013}_{-0.0135\,-0.0014}$	$-0.019^{+0.000\,+0.001}_{-0.000\,-0.001}$	$-0.0559^{+0.0045\,+0.0003}_{-0.0018\,-0.0005}$	$-0.020^{+0.000\,+0.000}_{-0.000\,-0.000}$	1.26
Quadratic	$\sigma_{\phi G,\phi G}$	$0.8178^{+0.2987\,+0.1718}_{-0.2032\,-0.1314}$	$0.353^{+0.016\,+0.074}_{-0.014\,-0.057}$	$1.6003^{+0.2802\,+0.1528}_{-0.2598\,-0.1286}$	$0.578^{+0.095\,+0.055}_{-0.058\,-0.046}$	1.96
Quadratic	$\sigma_{\phi G,tG}$	$1.5954^{+0.5561\,+0.1296}_{-0.3835\,-0.1132}$	$0.689^{+0.023\,+0.056}_{-0.020\,-0.049}$	$2.5519^{+0.2729\,+0.0593}_{-0.3254\,-0.0488}$	$0.922^{+0.089\,+0.021}_{-0.058\,-0.018}$	1.60
Quadratic	$\sigma_{\phi G,tW}$	$0.2548^{+0.0807\,+0.0268}_{-0.0571\,-0.0227}$	$0.110^{+0.001\,+0.012}_{-0.001\,-0.010}$	$0.4091^{+0.0508\,+0.0146}_{-0.0524\,-0.0120}$	$0.148^{+0.017\,+0.005}_{-0.009\,-0.004}$	1.61
Quadratic	$\sigma_{tG,tG}$	$3.4828^{+1.2967\,+0.0635}_{-0.8776\,-0.0700}$	$1.503^{+0.077\,+0.027}_{-0.066\,-0.030}$	$4.3143^{+0.0377\,+0.0225}_{-0.2985\,-0.0320}$	$1.559^{+0.009\,+0.008}_{-0.071\,-0.012}$	1.24
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- Overall, scale uncertainties reduce when going from LO to NLO…

$t\bar{t}H$ (dilepton): integrated cross sections

G.B, Reinartz and Worek, arXiv:2605.11747 [hep-ph]

$pp \to e^+\nu_e\,\mu^-\bar{\nu}_\mu\,b\bar{b}\,H + X$ (NWA) $\sqrt{s} = 13.6$ TeV

		$\sigma^{\rm LO}$[fb]	$\sigma^{\rm LO}/\sigma^{\rm LO}_{\rm SM}$	$\sigma^{\rm NLO}$[fb]	$\sigma^{\rm NLO}/\sigma^{\rm NLO}_{\rm SM}$	$\mathcal{K}$
	σ_{SM}	$2.3166^{+0.7068\,+0.0000}_{-0.5044\,-0.0000}$	$1.000^{+0.000\,+0.000}_{-0.000\,-0.000}$	$2.7680^{+0.0560\,+0.0000}_{-0.1898\,-0.0000}$	$1.000^{+0.000\,+0.000}_{-0.000\,-0.000}$	1.19
Linear	$\sigma_{t\phi}$	$-0.2835^{+0.0617\,+0.0122}_{-0.0865\,-0.0139}$	$-0.122^{+0.000\,+0.005}_{-0.000\,-0.006}$	$-0.3578^{+0.0287\,+0.0033}_{-0.0117\,-0.0045}$	$-0.129^{+0.002\,+0.001}_{-0.003\,-0.002}$	1.26
	$\sigma_{\phi G}$	$1.6262^{+0.5137\,+0.2000}_{-0.3638\,-0.1668}$	$0.702^{+0.006\,+0.086}_{-0.005\,-0.072}$	$2.6114^{+0.3238\,+0.1102}_{-0.3337\,-0.0919}$	$0.943^{+0.107\,+0.040}_{-0.060\,-0.033}$	1.61
	σ_{tG}	$2.4217^{+0.7568\,+0.0105}_{-0.5374\,-0.0131}$	$1.045^{+0.006\,+0.005}_{-0.006\,-0.006}$	$2.8196^{+0.0454\,+0.0130}_{-0.1757\,-0.0153}$	$1.019^{+0.007\,+0.005}_{-0.017\,-0.006}$	1.16
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Quadratic	$\sigma_{t\phi,t\phi}$	$0.0087^{+0.0026\,+0.0009}_{-0.0019\,-0.0007}$	$0.004^{+0.000\,+0.000}_{-0.000\,-0.000}$	$0.0115^{+0.0006\,+0.0003}_{-0.0010\,-0.0003}$	$0.004^{+0.000\,+0.000}_{-0.000\,-0.000}$	1.33
	$\sigma_{t\phi,\phi G}$	$-0.0995^{+0.0223\,+0.0140}_{-0.0314\,-0.0177}$	$-0.043^{+0.000\,+0.006}_{-0.000\,-0.008}$	$-0.1663^{+0.0223\,+0.0095}_{-0.0228\,-0.0110}$	$-0.060^{+0.004\,+0.003}_{-0.008\,-0.004}$	1.67
	$\sigma_{t\phi,tG}$	$-0.1482^{+0.0329\,+0.0058}_{-0.0463\,-0.0064}$	$-0.064^{+0.000\,+0.002}_{-0.000\,-0.003}$	$-0.1822^{+0.0136\,+0.0007}_{-0.0037\,-0.0011}$	$-0.066^{+0.000\,+0.000}_{-0.001\,-0.000}$	1.23
	$\sigma_{t\phi,tW}$	$-0.0443^{+0.0097\,+0.0013}_{-0.0135\,-0.0014}$	$-0.019^{+0.000\,+0.001}_{-0.000\,-0.001}$	$-0.0559^{+0.0045\,+0.0003}_{-0.0018\,-0.0005}$	$-0.020^{+0.000\,+0.000}_{-0.000\,-0.000}$	1.26
	$\sigma_{\phi G,\phi G}$	$0.8178^{+0.2987\,+0.1718}_{-0.2032\,-0.1314}$	$0.353^{+0.016\,+0.074}_{-0.014\,-0.057}$	$1.6003^{+0.2802\,+0.1528}_{-0.2598\,-0.1286}$	$0.578^{+0.095\,+0.055}_{-0.058\,-0.046}$	1.96
	$\sigma_{\phi G,tG}$	$1.5954^{+0.5561\,+0.1296}_{-0.3835\,-0.1132}$	$0.689^{+0.023\,+0.056}_{-0.020\,-0.049}$	$2.5519^{+0.2729\,+0.0593}_{-0.3254\,-0.0488}$	$0.922^{+0.089\,+0.021}_{-0.058\,-0.018}$	1.60
	$\sigma_{\phi G,tW}$	$0.2548^{+0.0807\,+0.0268}_{-0.0571\,-0.0227}$	$0.110^{+0.001\,+0.012}_{-0.001\,-0.010}$	$0.4091^{+0.0508\,+0.0146}_{-0.0524\,-0.0120}$	$0.148^{+0.017\,+0.005}_{-0.009\,-0.004}$	1.61
	$\sigma_{tG,tG}$	$3.4828^{+1.2967\,+0.0635}_{-0.8776\,-0.0700}$	$1.503^{+0.077\,+0.027}_{-0.066\,-0.030}$	$4.3143^{+0.0377\,+0.0225}_{-0.2985\,-0.0320}$	$1.559^{+0.009\,+0.008}_{-0.071\,-0.012}$	1.24
	$\sigma_{tG,tW}$	$0.3795^{+0.1189\,+0.0076}_{-0.0843\,-0.0084}$	$0.164^{+0.001\,+0.003}_{-0.001\,-0.004}$	$0.4412^{+0.0071\,+0.0029}_{-0.0274\,-0.0040}$	$0.159^{+0.001\,+0.001}_{-0.003\,-0.001}$	1.16
	$\sigma_{tW,tW}$	$0.0754^{+0.0231\,+0.0022}_{-0.0165\,-0.0024}$	$0.033^{+0.000\,+0.001}_{-0.000\,-0.001}$	$0.0895^{+0.0018\,+0.0004}_{-0.0060\,-0.0007}$	$0.032^{+0.000\,+0.000}_{-0.000\,-0.000}$	1.19

- … **with some notable exceptions**

$t\bar{t}H$ (dilepton): integrated cross sections

G.B, Reinartz and Worek, arXiv:2605.11747 [hep-ph]

$pp \to e^+\nu_e\,\mu^-\bar{\nu}_\mu\,b\bar{b}\,H + X$ (NWA) $\sqrt{s} = 13.6$ TeV

		$\sigma^{\rm LO}$[fb]	$\sigma^{\rm LO}/\sigma^{\rm LO}_{\rm SM}$	$\sigma^{\rm NLO}$[fb]	$\sigma^{\rm NLO}/\sigma^{\rm NLO}_{\rm SM}$	$\mathcal{K}$
	σ_{SM}	$2.3166^{+0.7068\,+0.0000}_{-0.5044\,-0.0000}$	$1.000^{+0.000\,+0.000}_{-0.000\,-0.000}$	$2.7680^{+0.0560\,+0.0000}_{-0.1898\,-0.0000}$	$1.000^{+0.000\,+0.000}_{-0.000\,-0.000}$	1.19
Linear	$\sigma_{t\phi}$	$-0.2835^{+0.0617\,+0.0122}_{-0.0865\,-0.0139}$	$-0.122^{+0.000\,+0.005}_{-0.000\,-0.006}$	$-0.3578^{+0.0287\,+0.0033}_{-0.0117\,-0.0045}$	$-0.129^{+0.002\,+0.001}_{-0.003\,-0.002}$	1.26
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	σ_{tW}	$0.7238^{+0.2214\,+0.0107}_{-0.1579\,-0.0115}$	$0.312^{+0.000\,+0.005}_{-0.000\,-0.005}$	$0.8669^{+0.0178\,+0.0019}_{-0.0600\,-0.0033}$	$0.313^{+0.000\,+0.001}_{-0.000\,-0.001}$	1.20
Quadratic	$\sigma_{t\phi,t\phi}$	$0.0087^{+0.0026\,+0.0009}_{-0.0019\,-0.0007}$	$0.004^{+0.000\,+0.000}_{-0.000\,-0.000}$	$0.0115^{+0.0006\,+0.0003}_{-0.0010\,-0.0003}$	$0.004^{+0.000\,+0.000}_{-0.000\,-0.000}$	1.33
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	$\sigma_{tW,tW}$	$0.0754^{+0.0231\,+0.0022}_{-0.0165\,-0.0024}$	$0.033^{+0.000\,+0.001}_{-0.000\,-0.001}$	$0.0895^{+0.0018\,+0.0004}_{-0.0060\,-0.0007}$	$0.032^{+0.000\,+0.000}_{-0.000\,-0.000}$	1.19

- K-factors quite differ in SMEFT contributions and in SM

$t\bar{t}H$ (dilepton): integrated cross sections

G.B, Reinartz and Worek, arXiv:2605.11747 [hep-ph]

	$pp \to e^+\nu_e\,\mu^-\bar{\nu}_\mu\,b\bar{b}\,H + X$ (NWA) $\sqrt{s} = 13.6$ TeV					
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	σ_{SM}	$2.3166^{+0.7068\,+0.0000}_{-0.5044\,-0.0000}$	$1.000^{+0.000\,+0.000}_{-0.000\,-0.000}$	$2.7680^{+0.0560\,+0.0000}_{-0.1898\,-0.0000}$	$1.000^{+0.000\,+0.000}_{-0.000\,-0.000}$	1.19
Linear	$\sigma_{t\phi}$	$-0.2835^{+0.0617\,+0.0122}_{-0.0865\,-0.0139}$	$-0.122^{+0.000\,+0.005}_{-0.000\,-0.006}$	$-0.3578^{+0.0287\,+0.0033}_{-0.0117\,-0.0045}$	$-0.129^{+0.002\,+0.001}_{-0.003\,-0.002}$	1.26
Linear	$\sigma_{\phi G}$	$1.6262^{+0.5137\,+0.2000}_{-0.3638\,-0.1668}$	$0.702^{+0.006\,+0.086}_{-0.005\,-0.072}$	$2.6114^{+0.3238\,+0.1102}_{-0.3337\,-0.0919}$	$0.943^{+0.107\,+0.040}_{-0.060\,-0.033}$	1.61
Linear	σ_{tG}	$2.4217^{+0.7568\,+0.0105}_{-0.5374\,-0.0131}$	$1.045^{+0.006\,+0.005}_{-0.006\,-0.006}$	$2.8196^{+0.0454\,+0.0130}_{-0.1757\,-0.0153}$	$1.019^{+0.007\,+0.005}_{-0.017\,-0.006}$	1.16
Linear	σ_{tW}	$0.7238^{+0.2214\,+0.0107}_{-0.1579\,-0.0115}$	$0.312^{+0.000\,+0.005}_{-0.000\,-0.005}$	$0.8669^{+0.0178\,+0.0019}_{-0.0600\,-0.0033}$	$0.313^{+0.000\,+0.001}_{-0.000\,-0.001}$	1.20
Quadratic	$\sigma_{t\phi,t\phi}$	$0.0087^{+0.0026\,+0.0009}_{-0.0019\,-0.0007}$	$0.004^{+0.000\,+0.000}_{-0.000\,-0.000}$	$0.0115^{+0.0006\,+0.0003}_{-0.0010\,-0.0003}$	$0.004^{+0.000\,+0.000}_{-0.000\,-0.000}$	1.33
Quadratic	$\sigma_{t\phi,\phi G}$	$-0.0995^{+0.0223\,+0.0140}_{-0.0314\,-0.0177}$	$-0.043^{+0.000\,+0.006}_{-0.000\,-0.008}$	$-0.1663^{+0.0223\,+0.0095}_{-0.0228\,-0.0110}$	$-0.060^{+0.004\,+0.003}_{-0.008\,-0.004}$	1.67
Quadratic	$\sigma_{t\phi,tG}$	$-0.1482^{+0.0329\,+0.0058}_{-0.0463\,-0.0064}$	$-0.064^{+0.000\,+0.002}_{-0.000\,-0.003}$	$-0.1822^{+0.0136\,+0.0007}_{-0.0037\,-0.0011}$	$-0.066^{+0.000\,+0.000}_{-0.001\,-0.000}$	1.23
Quadratic	$\sigma_{t\phi,tW}$	$-0.0443^{+0.0097\,+0.0013}_{-0.0135\,-0.0014}$	$-0.019^{+0.000\,+0.001}_{-0.000\,-0.001}$	$-0.0559^{+0.0045\,+0.0003}_{-0.0018\,-0.0005}$	$-0.020^{+0.000\,+0.000}_{-0.000\,-0.000}$	1.26
Quadratic	$\sigma_{\phi G,\phi G}$	$0.8178^{+0.2987\,+0.1718}_{-0.2032\,-0.1314}$	$0.353^{+0.016\,+0.074}_{-0.014\,-0.057}$	$1.6003^{+0.2802\,+0.1528}_{-0.2598\,-0.1286}$	$0.578^{+0.095\,+0.055}_{-0.058\,-0.046}$	1.96
Quadratic	$\sigma_{\phi G,tG}$	$1.5954^{+0.5561\,+0.1296}_{-0.3835\,-0.1132}$	$0.689^{+0.023\,+0.056}_{-0.020\,-0.049}$	$2.5519^{+0.2729\,+0.0593}_{-0.3254\,-0.0488}$	$0.922^{+0.089\,+0.021}_{-0.058\,-0.018}$	1.60
Quadratic	$\sigma_{\phi G,tW}$	$0.2548^{+0.0807\,+0.0268}_{-0.0571\,-0.0227}$	$0.110^{+0.001\,+0.012}_{-0.001\,-0.010}$	$0.4091^{+0.0508\,+0.0146}_{-0.0524\,-0.0120}$	$0.148^{+0.017\,+0.005}_{-0.009\,-0.004}$	1.61
Quadratic	$\sigma_{tG,tG}$	$3.4828^{+1.2967\,+0.0635}_{-0.8776\,-0.0700}$	$1.503^{+0.077\,+0.027}_{-0.066\,-0.030}$	$4.3143^{+0.0377\,+0.0225}_{-0.2985\,-0.0320}$	$1.559^{+0.009\,+0.008}_{-0.071\,-0.012}$	1.24
Quadratic	$\sigma_{tG,tW}$	$0.3795^{+0.1189\,+0.0076}_{-0.0843\,-0.0084}$	$0.164^{+0.001\,+0.003}_{-0.001\,-0.004}$	$0.4412^{+0.0071\,+0.0029}_{-0.0274\,-0.0040}$	$0.159^{+0.001\,+0.001}_{-0.003\,-0.001}$	1.16
Quadratic	$\sigma_{tW,tW}$	$0.0754^{+0.0231\,+0.0022}_{-0.0165\,-0.0024}$	$0.033^{+0.000\,+0.001}_{-0.000\,-0.001}$	$0.0895^{+0.0018\,+0.0004}_{-0.0060\,-0.0007}$	$0.032^{+0.000\,+0.000}_{-0.000\,-0.000}$	1.19

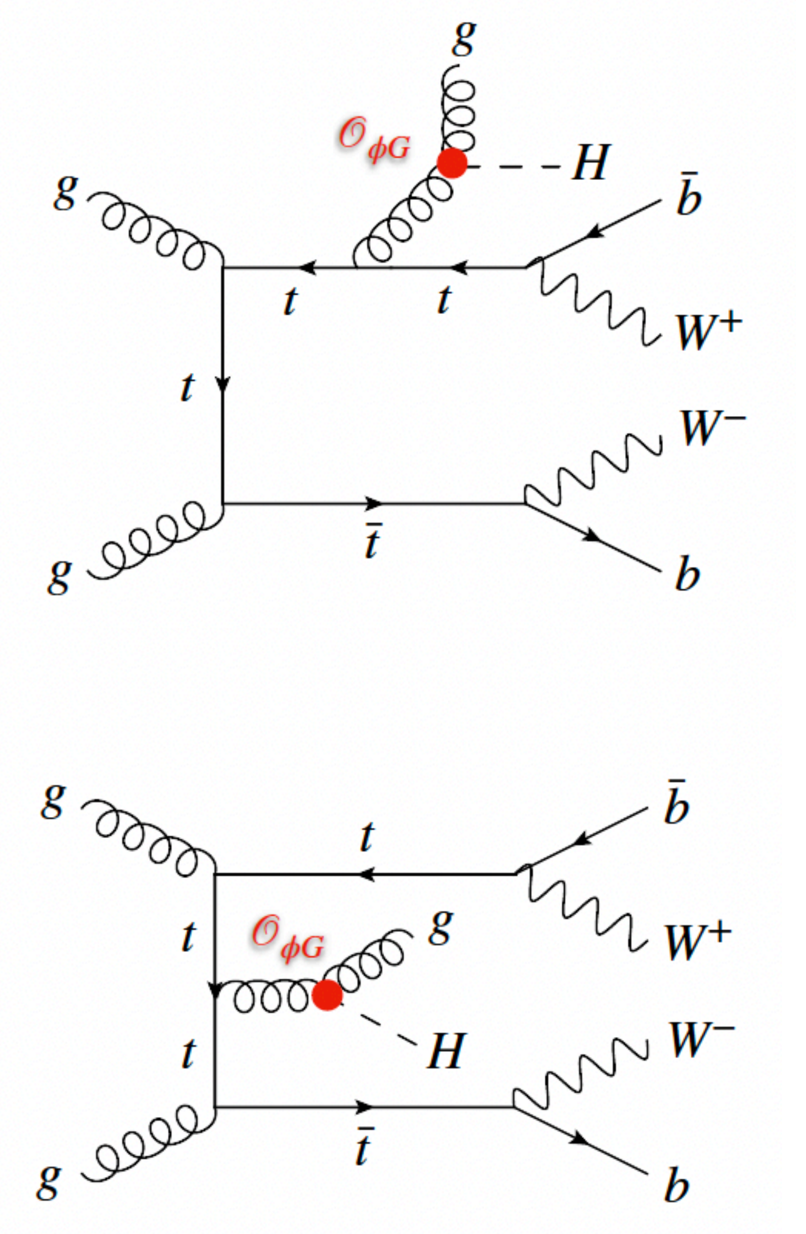
- Large K-factors in SMEFT contributions induced by $\mathcal{O}_{\phi G}$
- These contributions feature also larger NLO scale dependence

$t\bar{t}H$ (dilepton): origin of large K-factors

- Large K-factors in $\mathcal{O}_{\phi G}$ contributions stem from $g \to gH$ splittings in real-radiation contributions

- Check — impose jet veto on the extra jet from QCD radiation:

p_T^{veto} [GeV]		$\sigma^{\rm LO}$ [fb]	$\sigma^{\rm NLO}$ [fb]	$\mathcal{K}$
-	$\sigma_{\rm SM}$	$2.3166^{+0.7068\,+0.0000}_{-0.5044\,-0.0000}$	$2.7680^{+0.0560\,+0.0000}_{-0.1898\,-0.0000}$	1.19
	$\sigma_{\phi G}$	$1.6262^{+0.5137\,+0.2089}_{-0.3638\,-0.1730}$	$2.5292^{+0.2865\,+0.1154}_{-0.3098\,-0.0954}$	1.56
	$\sigma_{\phi G,\phi G}$	$0.8178^{+0.2987\,+0.1799}_{-0.2032\,-0.1361}$	$1.5299^{+0.2443\,+0.1528}_{-0.2377\,-0.1277}$	1.87
150	$\sigma_{\rm SM}$	$2.3166^{+0.7068\,+0.0000}_{-0.5044\,-0.0000}$	$2.2694^{+0.0171\,+0.0000}_{-0.2326\,-0.0000}$	0.98
	$\sigma_{\phi G}$	$1.6262^{+0.5137\,+0.2089}_{-0.3638\,-0.1730}$	$2.0748^{+0.0601\,+0.0583}_{-0.1642\,-0.0486}$	1.28
	$\sigma_{\phi G,\phi G}$	$0.8178^{+0.2987\,+0.1799}_{-0.2032\,-0.1361}$	$1.2207^{+0.0738\,+0.0840}_{-0.1339\,-0.0761}$	1.49
100	$\sigma_{\rm SM}$	$2.3166^{+0.7068\,+0.0000}_{-0.5044\,-0.0000}$	$1.9589^{+0.0652\,+0.0000}_{-0.3863\,-0.0000}$	0.85
	$\sigma_{\phi G}$	$1.6262^{+0.5137\,+0.2089}_{-0.3638\,-0.1730}$	$1.8239^{+0.0032\,+0.0259}_{-0.0863\,-0.0220}$	1.12
	$\sigma_{\phi G,\phi G}$	$0.8178^{+0.2987\,+0.1799}_{-0.2032\,-0.1361}$	$1.0616^{+0.0209\,+0.0483}_{-0.0815\,-0.0494}$	1.30



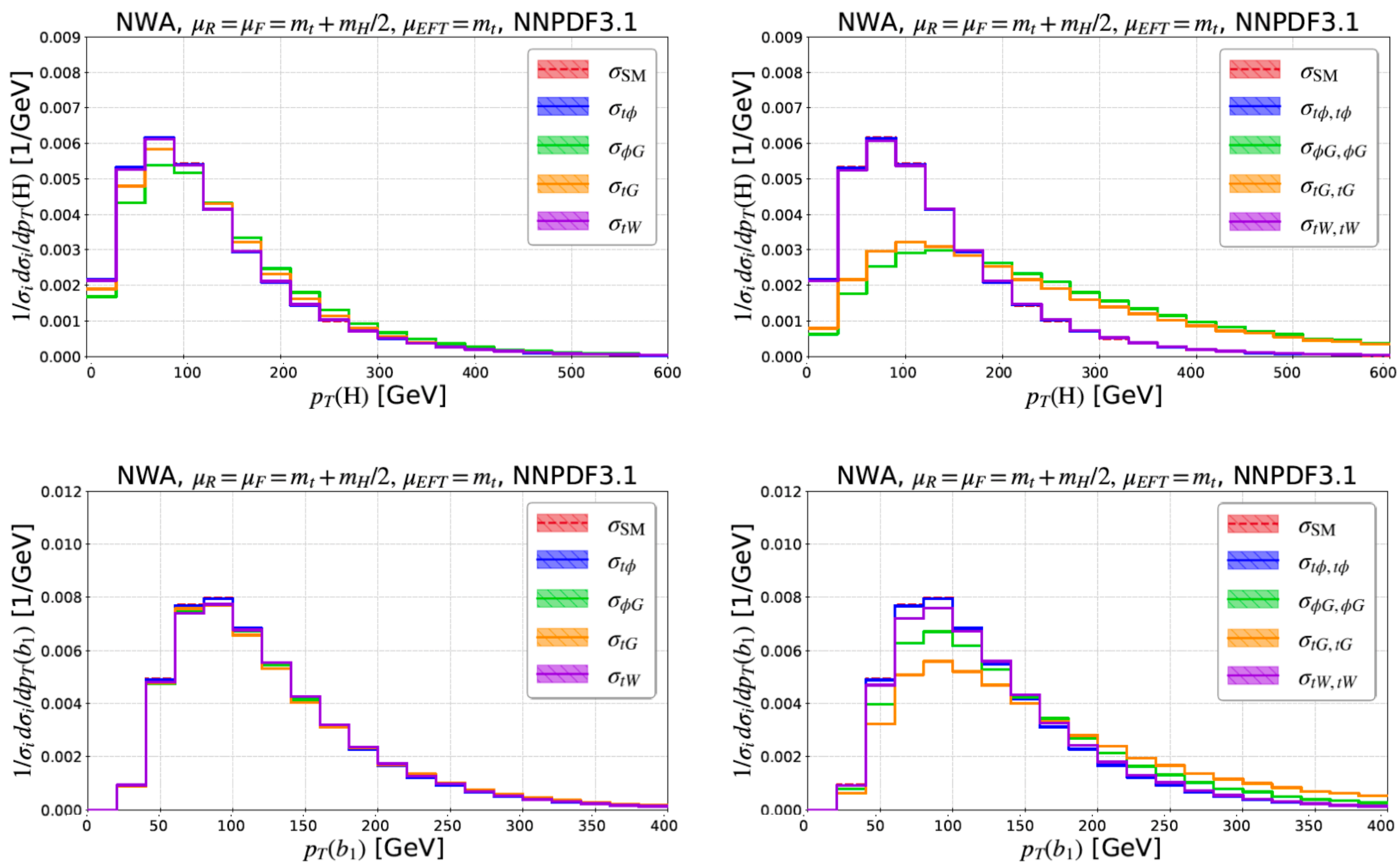
G.B, Reinartz and Worek, arXiv:2605.11747 [hep-ph]

- How SMEFT affects *shapes*: normalised NLO distributions

Linear | Quadratic

$p_T(H)$ →

$p_T(b_1)$ →

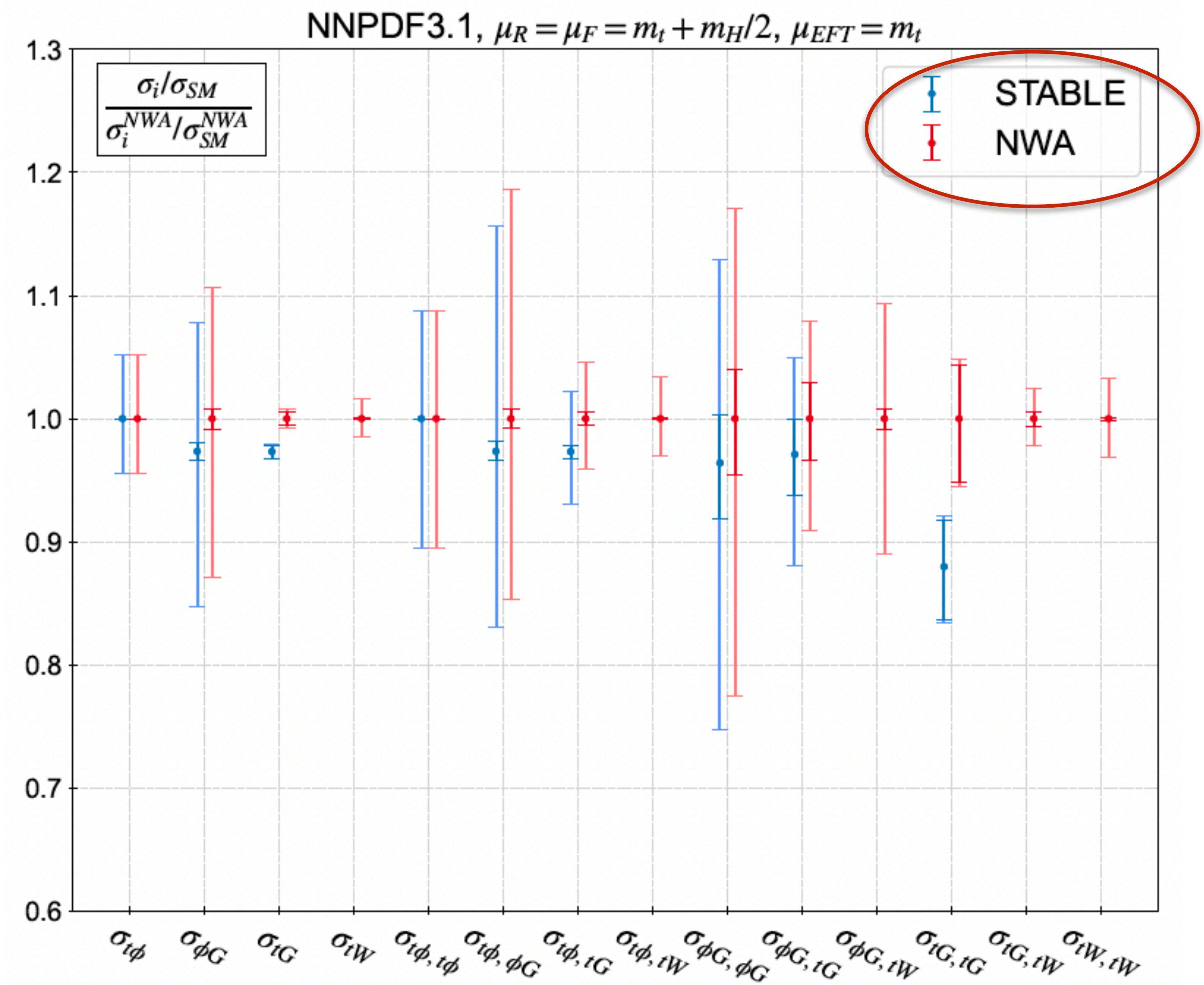


G.B, Reinartz and Worek, arXiv:2605.11747 [hep-ph]

Comparing NWA vs stable-top predictions

- "Double-ratio plot": how robust is the ratio to SM against different modelling approaches ?

LO

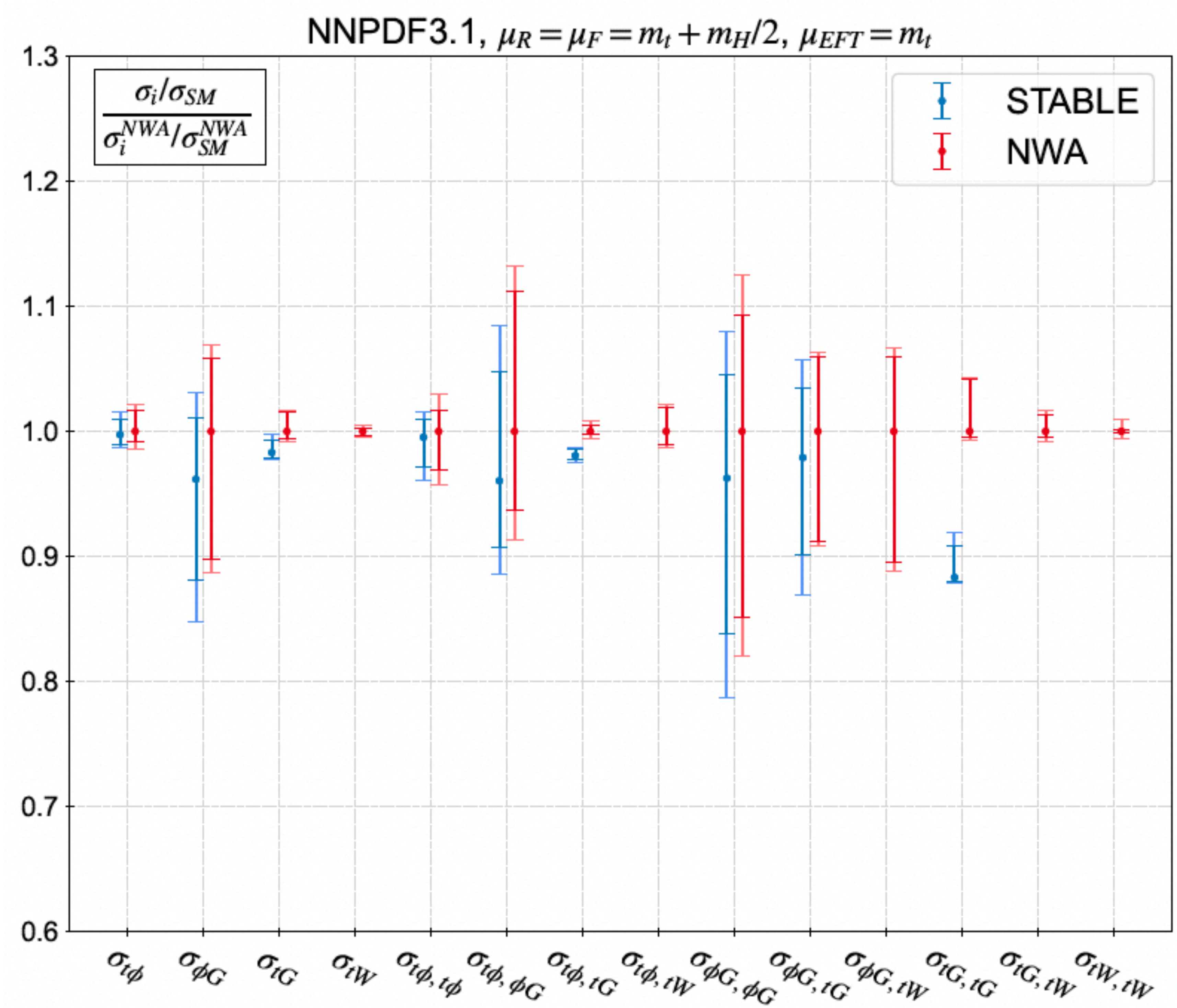


G.B, Reinartz and Worek, arXiv:2605.11747 [hep-ph]

Comparing NWA vs stable-top predictions

- “Double-ratio plot”: how robust is the ratio to SM against different modelling approaches ?

NLO



G.B, Reinartz and Worek, arXiv:2605.11747 [hep-ph]

Summary and outlook

- We have presented a NLO QCD study of $pp \to t\bar{t}H$ in dilepton decay channel at the LHC, based on dimension-6 SMEFT operators $\mathcal{O}_{t\phi}$, $\mathcal{O}_{\phi G}$, $\mathcal{O}_{tG}$, $\mathcal{O}_{tW}$
- Kinematic cuts, SMEFT contributions, and NLO QCD corrections in top-quark decays have been simultaneously considered for the first time
- Differences in size of SMEFT contributions, K-factors and magnitude of theoretical uncertainties have been observed
- To distinguish all these aspects, it is necessary to perform more detailed comparisons of NLO results based on different modelling approaches to top-quark decays

Future work

- Explore dynamic (i.e. phase space dependent) scales to improve pert. convergence
- Explore more exclusive fiducial cuts to check robustness of our predictions
- Disentangle and quantify individual contributions from NLO corrections / SMEFT effects to top-quark decays as well as kinematic cuts

Thank you for your attention!

감사합니다!

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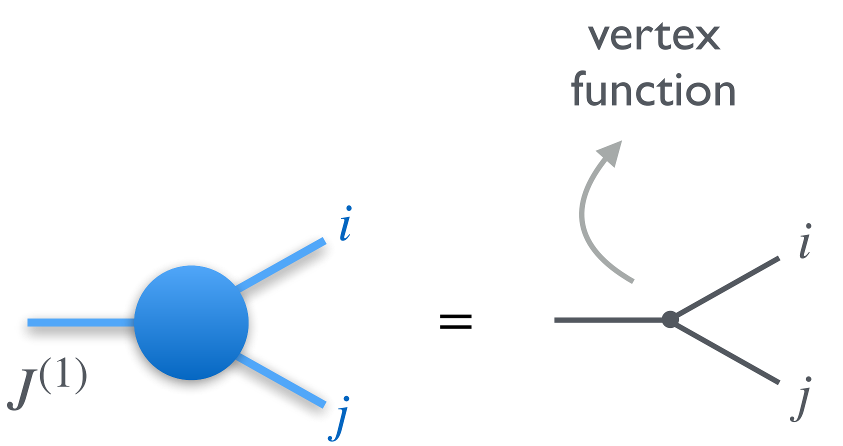
Backup slides

Recursive helicity amplitude calculations



- The building blocks of recursive calculations are (off-shell) *currents* ($J^{(N)}$)
- At each step of the recursion, a new current $J^{(N)}$ is computed, representing a *sub-amplitude*
- Recursion iterates till the *full amplitude* is constructed