Constraining SMEFT four-quark operators via Higgs+jet production at NLO

Higgs2022, Pisa

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Introduction

- The Standard Model (SM) leaves several phenomena unexplained.
- None of the proposed theories beyond the SM (BSM) has empirical support (to date).
- The Standard Model Effective Field Theory (SMEFT) provides a powerful and pragmatic approach to the search for heavy new physics.

The Standard Model Effective Field Theory (SMEFT)

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- BSM effects are encoded in the coefficients of Lorentz and gauge-invariant higher-dimensional operators C_i:

$$\mathcal{L}_{\text{SMEFT}} = \mathcal{L}_{\text{SM}} + \sum_{\mathfrak{D}_i > 4} C_i \mathcal{O}_i = \mathcal{L}_{\text{SM}} + \sum_{\mathfrak{D}_i > 4} \frac{c_i}{\Lambda^{\mathfrak{D}_i - 4}} \mathcal{O}_i .$$

- The operators $\mathcal{O}_i$ are built using only SM fields.

- The gauge group and the transformation properties of the fields are the same of the SM:

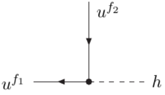
$$\text{SU}(3)_{\text{C}} \otimes \text{SU}(2)_{\text{W}} \otimes \text{U}(1)_{\text{Y}} .$$

The SMEFT at dimension-six level

- At $\mathfrak{D} = 6$ a complete basis of independent and gauge invariant operators (that preserve baryon and lepton number) is given by the **Warsaw basis** [Grzadkowski,Iskrzynski,Misiak,Rosiek,'10].
- 59 independent operators, 2499 when the flavour structure is considered.

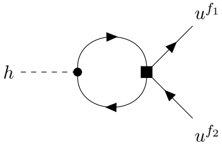
Impact of SMEFT operators

- Insertions of SMEFT operators change the interaction vertices with $\mathcal{O}\left(1/\Lambda^2\right)$ corrections [Dedes,Materkowska,Paraskevas,Rosiek,Suxho,'17] .



$$-\frac{i}{v}\delta_{f_1f_2}m_{u_{f_1}} - iv\delta_{f_1f_2}C^{\varphi\Box}m_{u_{f_1}} + \frac{iv}{4}\delta_{f_1f_2}C^{\varphi D}m_{u_{f_1}} + \frac{iv^2}{\sqrt{2}}\left(P_L C^{u\varphi*}_{f_2f_1} + P_R C^{u\varphi}_{f_1f_2}\right)$$

- They also modify the running of SM parameters via loop effects [Jenkins,Manohar,Trott,'13].



Framework

- We focus on 4 top operators.

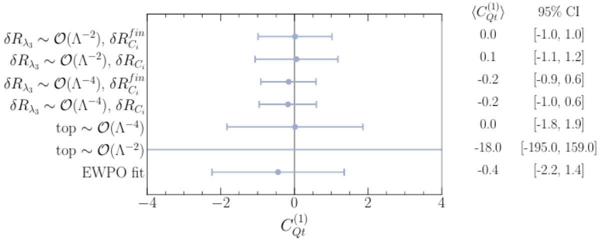
- The Lagrangian at the heavy new physics scale Λ is:

$$\begin{aligned}\mathcal{L}_{\mathfrak{D}=6} = & \; C_{tt}(\bar{t}_R\gamma^\mu t_R)(\bar{t}_R\gamma_\mu t_R) \\ & + C_{QQ1}(\bar{Q}_L\gamma^\mu Q_L)(\bar{Q}_L\gamma_\mu Q_L) \\ & + C_{QQ3}(\bar{Q}_L\gamma^\mu\tau^I Q_L)(\bar{Q}_L\gamma_\mu\tau^I Q_L) \\ & + C_{Qt1}(\bar{Q}_L\gamma^\mu Q_L)(\bar{t}_R\gamma_\mu t_R) \\ & + C_{Qt8}(\bar{Q}_L\gamma^\mu T^A Q_L)(\bar{t}_R\gamma_\mu T^A t_R).\end{aligned}$$

- We want to test their impact in the p_T distribution of the Higgs+jet production in a pp collider.

State-of-the-art

- Indirect bounds from single Higgs production ([Alasfar,de Blas,Gröber,'22]) are competitive with the ones from top quark data ([Ethier et. al.,'21]) and from EWPO ([Dawson,Giardino,'22]).



[Alasfar,de Blas,Gröber,'22]

- Some operators can also be constrained from flavour observables ([Silvestrini,Valli,'18]).

Relevant partonic processes

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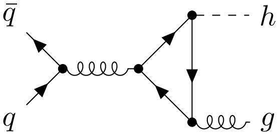
- An Higgs boson and a jet are produced via different partonic channels: $\bar{q}q \to gh$, $qg \to qh$, $\bar{q}g \to \bar{q}h$, $gg \to gh$.

- In this talk I will focus on quark-initiated channels.

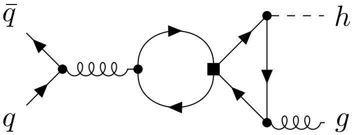
- $qg \to qh$ and $\bar{q}g \to \bar{q}h$ can be obtained by crossing from $\bar{q}q \to gh$.

- The hadronic cross section is then obtained with:

$$\sigma_{\text{Had}}(pp \to hj) = \sum_{\text{X}} \int dx_1 dx_2 f(x_1) f(x_2) \sigma_{\text{Par}}(X \to hj).$$



- One of the diagrams contributing to the LO amplitude (2 in total).



- One of the diagrams contributing to the NLO amplitude (12 in total).

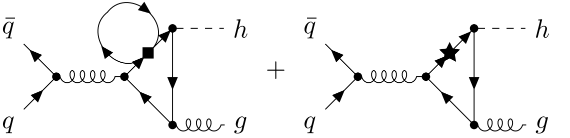
- We consider only the contribution of the top quark in the loops.

Computation of NLO matrix element

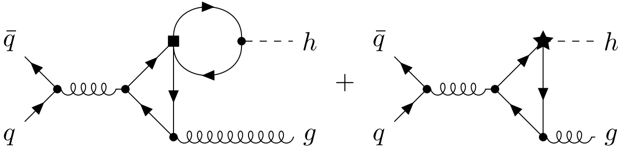
- The computation is performed via a computer program, using:
  - `qgraf-3.4.2` to generate the amplitudes,
  - `FORM` to carry on the color and Dirac algebra,
  - `kira 1.2` to perform the IBP reduction.
- The result is cross-checked using `FeynArts` and `FIRE`.
- Currently, the cross-check has been performed for the operators $\mathcal{O}_{tt}$, $\mathcal{O}_{QQ1}$, $\mathcal{O}_{QQ3}$.

Renormalization

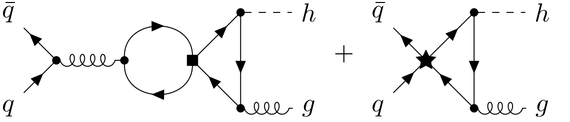
- The 12 diagrams can be divided in 3 categories:



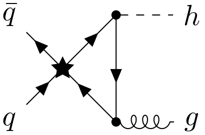
$< \infty,$



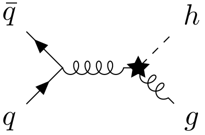
$< \infty,$



$= \infty.$



- The counterterms from $(\bar{q}q\bar{t}t)$ operators don't remove all the divergencies.



- We found a 2 loop counterterm for the operator $\mathcal{O}_{HG}$:

$$\delta_{HG} = \left(C_{Qt8} - 6C_{Qt1}\right)\frac{g_s^2 m_t^2}{3\,(16\pi^2)^2 \epsilon v^2}.$$

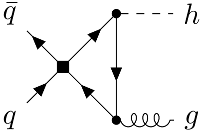
- The same counterterm was found by J. Lang, G. Heinrich (see J.L.'s talk on Wednesday).

Phenomenological consequences of the 4 top operators

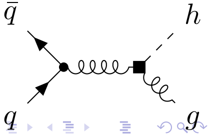
- 4 top operators modify the Higgs + jet production via the NLO amplitude.
- $\neq 0$ 4 top operators at $\mu = \Lambda$ generate via operator mixing $\bar{q}q\bar{t}t$, ggh vertices at $\mu = \mu_{\text{Low}} = \frac{\sqrt{p_T^2 + m_h^2}}{2}$.
- Operator mixing generates also $C_{uH}^{3,3}(\mu_{\text{Low}}) \neq 0$, leading to a modification of the $h\bar{t}t$ vertex.

$$\mathcal{M}_{\text{TOT}} = \mathcal{M}_{\text{LO}}(1 + \underbrace{\Delta_{\mathcal{M}}}_{\mathcal{O}\left(\frac{v^2}{\Lambda^2}\right)}) + \underbrace{\mathcal{M}_{\text{NLO}}}_{\mathcal{O}\left(\frac{v^2}{\Lambda^2}\right)} + \underbrace{\mathcal{M}_{\bar{q}q\bar{t}t}}_{\mathcal{O}\left(\frac{v^2}{\Lambda^2}\right)} + \underbrace{\mathcal{M}_{HG}}_{\mathcal{O}\left(\frac{v^2}{\Lambda^2}\right)} .$$

$\mathcal{M}_{\bar{q}q\bar{t}t} =$



$i\mathcal{M}_{HG} =$



Results

- We implemented a FORTRAN program to perform the integration on the partonic momenta, using:
  - VEGAS to perform the Monte Carlo integration,
  - NNPDF30_lo_as_0118 set (accessed via LHAPDF-6.5.1).
- The running effects of the Wilson coefficients in SMEFT have been computed with a C++ program that uses RGESolver [S.D.N., Silvestrini,'22].
- The following plots have been obtained with:

$$C_X(\Lambda) = \frac{1}{\Lambda^2},\ \Lambda = 1\,\text{TeV} \quad (X = tt, QQ1, QQ3, Qt1, Qt8),$$

$$E_{\text{C.M.}} = 13\,\text{TeV}.$$

Transverse momentum distribution (preliminary)

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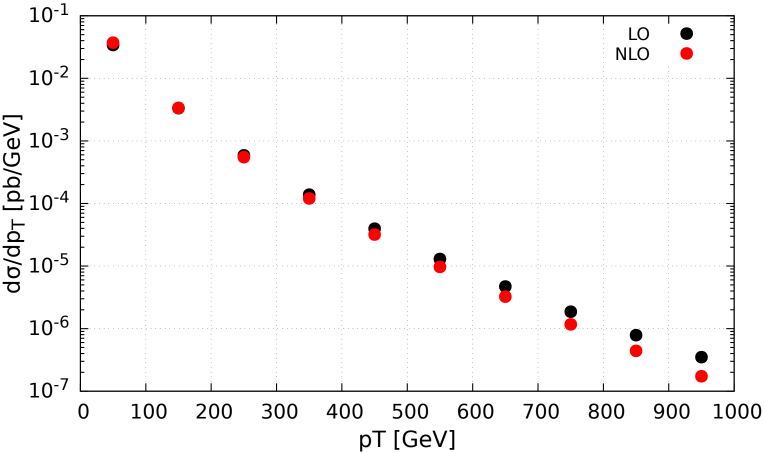
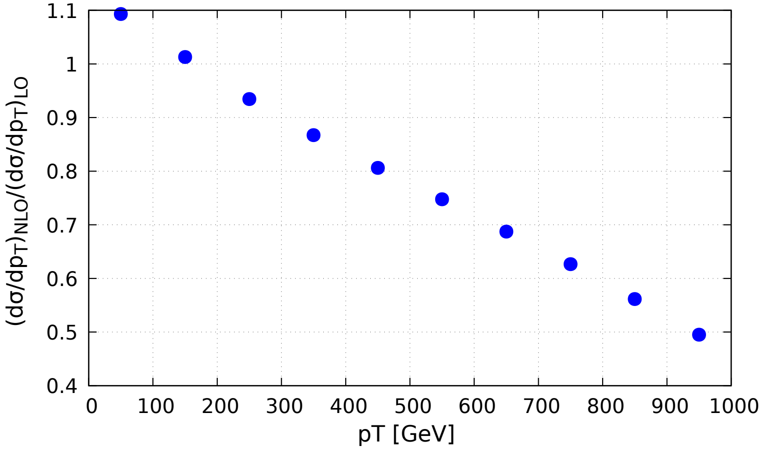
- The SMEFT
- 4t operators in $h + j$
- **Preliminary results**
- Outlook
- RGESolver
- Backup



Transverse momentum distribution (preliminary)



Outlook

- The next step will be completing the computation for the gluon fusion channel $gg \to gh$ (work in progress).
- Our plans are to perform a fit to put bounds on 4 top operators.

RGESolver

- A C++ library that performs renormalization group evolution of SMEFT coefficients.
- General flavour structure (assuming lepton and baryon number conservation).
- Numerical and approximate (first leading log) solutions of the RGEs are available.
- Back-rotation effects can be included ([Aebischer,Kumar,'20]).
- High time efficiency.

- Authors:
  - Stefano Di Noi,
  - Luca Silvestrini.

Transformation properties of the SM fields

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Field	$(\mathbf{R}_\mathrm{C}, \mathbf{R}_\mathrm{W})_\mathrm{y}$
q^p	$(\mathbf{3}, \mathbf{2})_{+\frac{1}{6}}$
l^p	$(\mathbf{1}, \mathbf{2})_{-\frac{1}{2}}$
u^p	$(\mathbf{3}, \mathbf{1})_{+\frac{2}{3}}$
d^p	$(\mathbf{3}, \mathbf{1})_{-\frac{1}{3}}$
e^p	$(\mathbf{1}, \mathbf{1})_{-1}$

Field	$(\mathbf{R}_\mathrm{C}, \mathbf{R}_\mathrm{W})_\mathrm{y}$
H	$(\mathbf{1}, \mathbf{2})_{+\frac{1}{2}}$
G^a_μ	$(\mathbf{8}, \mathbf{1})_0$
W^I_μ	$(\mathbf{1}, \mathbf{3})_0$
B_μ	$(\mathbf{1}, \mathbf{1})_0$

The Warsaw Basis

X^3		φ^6 and $\varphi^4 D^2$		$\psi^2\varphi^3$	
Q_G	$f^{ABC} G_\mu^{A\nu} G_\nu^{B\rho} G_\rho^{C\mu}$	Q_φ	$(\varphi^\dagger\varphi)^3$	$Q_{e\varphi}$	$(\varphi^\dagger\varphi)(\bar l_p e_r \varphi)$
$Q_{\widetilde G}$	$f^{ABC} \widetilde G_\mu^{A\nu} G_\nu^{B\rho} G_\rho^{C\mu}$	$Q_{\varphi\Box}$	$(\varphi^\dagger\varphi)\Box(\varphi^\dagger\varphi)$	$Q_{u\varphi}$	$(\varphi^\dagger\varphi)(\bar q_p u_r \widetilde\varphi)$
Q_W	$\varepsilon^{IJK} W_\mu^{I\nu} W_\nu^{J\rho} W_\rho^{K\mu}$	$Q_{\varphi D}$	$\left(\varphi^\dagger D^\mu\varphi\right)^\star \left(\varphi^\dagger D_\mu\varphi\right)$	$Q_{d\varphi}$	$(\varphi^\dagger\varphi)(\bar q_p d_r \varphi)$
$Q_{\widetilde W}$	$\varepsilon^{IJK} \widetilde W_\mu^{I\nu} W_\nu^{J\rho} W_\rho^{K\mu}$				
$X^2\varphi^2$		$\psi^2 X\varphi$		$\psi^2\varphi^2 D$	
$Q_{\varphi G}$	$\varphi^\dagger\varphi\, G^A_{\mu\nu} G^{A\mu\nu}$	Q_{eW}	$(\bar l_p \sigma^{\mu\nu} e_r)\tau^I \varphi W^I_{\mu\nu}$	$Q_{\varphi l}^{(1)}$	$(\varphi^\dagger i\overleftrightarrow{D}_\mu \varphi)(\bar l_p \gamma^\mu l_r)$
$Q_{\varphi\widetilde G}$	$\varphi^\dagger\varphi\, \widetilde G^A_{\mu\nu} G^{A\mu\nu}$	Q_{eB}	$(\bar l_p \sigma^{\mu\nu} e_r)\varphi B_{\mu\nu}$	$Q_{\varphi l}^{(3)}$	$(\varphi^\dagger i\overleftrightarrow{D}^I_\mu \varphi)(\bar l_p \tau^I \gamma^\mu l_r)$
$Q_{\varphi W}$	$\varphi^\dagger\varphi\, W^I_{\mu\nu} W^{I\mu\nu}$	Q_{uG}	$(\bar q_p \sigma^{\mu\nu} T^A u_r)\widetilde\varphi\, G^A_{\mu\nu}$	$Q_{\varphi e}$	$(\varphi^\dagger i\overleftrightarrow{D}_\mu \varphi)(\bar e_p \gamma^\mu e_r)$
$Q_{\varphi\widetilde W}$	$\varphi^\dagger\varphi\, \widetilde W^I_{\mu\nu} W^{I\mu\nu}$	Q_{uW}	$(\bar q_p \sigma^{\mu\nu} u_r)\tau^I \widetilde\varphi\, W^I_{\mu\nu}$	$Q_{\varphi q}^{(1)}$	$(\varphi^\dagger i\overleftrightarrow{D}_\mu \varphi)(\bar q_p \gamma^\mu q_r)$
$Q_{\varphi B}$	$\varphi^\dagger\varphi\, B_{\mu\nu} B^{\mu\nu}$	Q_{uB}	$(\bar q_p \sigma^{\mu\nu} u_r)\widetilde\varphi\, B_{\mu\nu}$	$Q_{\varphi q}^{(3)}$	$(\varphi^\dagger i\overleftrightarrow{D}^I_\mu \varphi)(\bar q_p \tau^I \gamma^\mu q_r)$
$Q_{\varphi\widetilde B}$	$\varphi^\dagger\varphi\, \widetilde B_{\mu\nu} B^{\mu\nu}$	Q_{dG}	$(\bar q_p \sigma^{\mu\nu} T^A d_r)\varphi\, G^A_{\mu\nu}$	$Q_{\varphi u}$	$(\varphi^\dagger i\overleftrightarrow{D}_\mu \varphi)(\bar u_p \gamma^\mu u_r)$
$Q_{\varphi WB}$	$\varphi^\dagger\tau^I\varphi\, W^I_{\mu\nu} B^{\mu\nu}$	Q_{dW}	$(\bar q_p \sigma^{\mu\nu} d_r)\tau^I \varphi\, W^I_{\mu\nu}$	$Q_{\varphi d}$	$(\varphi^\dagger i\overleftrightarrow{D}_\mu \varphi)(\bar d_p \gamma^\mu d_r)$
$Q_{\varphi\widetilde WB}$	$\varphi^\dagger\tau^I\varphi\, \widetilde W^I_{\mu\nu} B^{\mu\nu}$	Q_{dB}	$(\bar q_p \sigma^{\mu\nu} d_r)\varphi\, B_{\mu\nu}$	$Q_{\varphi ud}$	$i(\widetilde\varphi^\dagger D_\mu\varphi)(\bar u_p \gamma^\mu d_r)$

The Warsaw Basis

$(\bar{L}L)(\bar{L}L)$		$(\bar{R}R)(\bar{R}R)$		$(\bar{L}L)(\bar{R}R)$	
Q_{ll}	$(\bar{l}_p\gamma_\mu l_r)(\bar{l}_s\gamma^\mu l_t)$	Q_{ee}	$(\bar{e}_p\gamma_\mu e_r)(\bar{e}_s\gamma^\mu e_t)$	Q_{le}	$(\bar{l}_p\gamma_\mu l_r)(\bar{e}_s\gamma^\mu e_t)$
$Q_{qq}^{(1)}$	$(\bar{q}_p\gamma_\mu q_r)(\bar{q}_s\gamma^\mu q_t)$	Q_{uu}	$(\bar{u}_p\gamma_\mu u_r)(\bar{u}_s\gamma^\mu u_t)$	Q_{lu}	$(\bar{l}_p\gamma_\mu l_r)(\bar{u}_s\gamma^\mu u_t)$
$Q_{qq}^{(3)}$	$(\bar{q}_p\gamma_\mu \tau^I q_r)(\bar{q}_s\gamma^\mu \tau^I q_t)$	Q_{dd}	$(\bar{d}_p\gamma_\mu d_r)(\bar{d}_s\gamma^\mu d_t)$	Q_{ld}	$(\bar{l}_p\gamma_\mu l_r)(\bar{d}_s\gamma^\mu d_t)$
$Q_{lq}^{(1)}$	$(\bar{l}_p\gamma_\mu l_r)(\bar{q}_s\gamma^\mu q_t)$	Q_{eu}	$(\bar{e}_p\gamma_\mu e_r)(\bar{u}_s\gamma^\mu u_t)$	Q_{qe}	$(\bar{q}_p\gamma_\mu q_r)(\bar{e}_s\gamma^\mu e_t)$
$Q_{lq}^{(3)}$	$(\bar{l}_p\gamma_\mu \tau^I l_r)(\bar{q}_s\gamma^\mu \tau^I q_t)$	Q_{ed}	$(\bar{e}_p\gamma_\mu e_r)(\bar{d}_s\gamma^\mu d_t)$	$Q_{qu}^{(1)}$	$(\bar{q}_p\gamma_\mu q_r)(\bar{u}_s\gamma^\mu u_t)$
		$Q_{ud}^{(1)}$	$(\bar{u}_p\gamma_\mu u_r)(\bar{d}_s\gamma^\mu d_t)$	$Q_{qu}^{(8)}$	$(\bar{q}_p\gamma_\mu T^A q_r)(\bar{u}_s\gamma^\mu T^A u_t)$
		$Q_{ud}^{(8)}$	$(\bar{u}_p\gamma_\mu T^A u_r)(\bar{d}_s\gamma^\mu T^A d_t)$	$Q_{qd}^{(1)}$	$(\bar{q}_p\gamma_\mu q_r)(\bar{d}_s\gamma^\mu d_t)$
				$Q_{qd}^{(8)}$	$(\bar{q}_p\gamma_\mu T^A q_r)(\bar{d}_s\gamma^\mu T^A d_t)$

$(\bar{L}R)(\bar{R}L)$ and $(\bar{L}R)(\bar{L}R)$		B-violating	
Q_{ledq}	$(\bar{l}_p^j e_r)(\bar{d}_s q_t^j)$	Q_{duq}	$\varepsilon^{\alpha\beta\gamma}\varepsilon_{jk}\left[(d_p^\alpha)^T C u_r^\beta\right]\left[(q_s^{\gamma j})^T C l_t^k\right]$
$Q_{quqd}^{(1)}$	$(\bar{q}_p^j u_r)\varepsilon_{jk}(\bar{q}_s^k d_t)$	Q_{qqu}	$\varepsilon^{\alpha\beta\gamma}\varepsilon_{jk}\left[(q_p^{\alpha j})^T C q_r^{\beta k}\right]\left[(u_s^\gamma)^T C e_t\right]$
$Q_{quqd}^{(8)}$	$(\bar{q}_p^j T^A u_r)\varepsilon_{jk}(\bar{q}_s^k T^A d_t)$	Q_{qqq}	$\varepsilon^{\alpha\beta\gamma}\varepsilon_{jn}\varepsilon_{km}\left[(q_p^{\alpha j})^T C q_r^{\beta k}\right]\left[(q_s^{\gamma m})^T C l_t^n\right]$
$Q_{lequ}^{(1)}$	$(\bar{l}_p^j e_r)\varepsilon_{jk}(\bar{q}_s^k u_t)$	Q_{duu}	$\varepsilon^{\alpha\beta\gamma}\left[(d_p^\alpha)^T C u_r^\beta\right]\left[(u_s^\gamma)^T C e_t\right]$
$Q_{lequ}^{(3)}$	$(\bar{l}_p^j \sigma_{\mu\nu} e_r)\varepsilon_{jk}(\bar{q}_s^k \sigma^{\mu\nu} u_t)$		