HIGGS PRODUCTION AT NLO IN THE STANDARD MODEL EFT

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In collaboration with

Claude Duhr, **Fabio Maltoni** and **Eleni Vryonidou**

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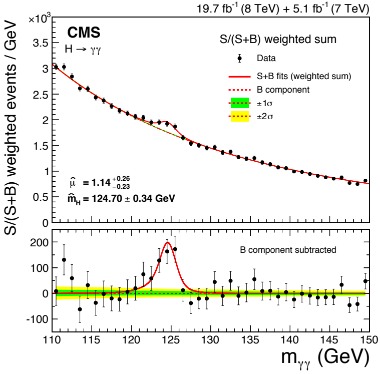
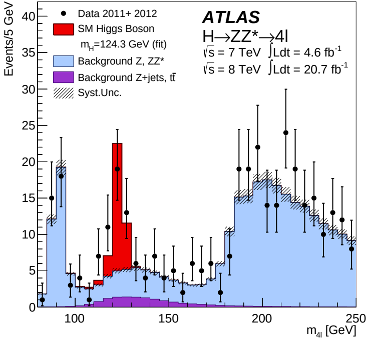
Constraining the Higgs boson at the LHC

Convincing evidence for the new LHC boson to be a CP-even scalar with SM-Higgs like properties.





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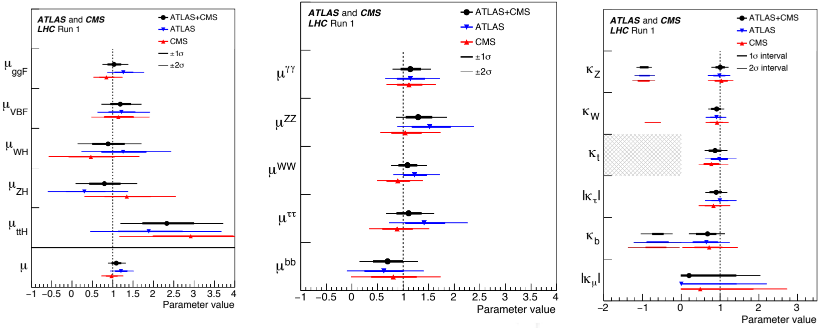

Measurements of signal strengths and κ parameters from Run I

Kappas VS couplings

The κ parameters are not the coefficients of a QFT, they are fit parameters:

$$\mathcal{N}_{\text{events}}(pp \to t\bar{t}H \to b\bar{b}) \underset{\text{fit}}{\longrightarrow} \kappa_t^2 \kappa_b^2 \left(\sigma \times B\right) \epsilon \mathcal{L} + \dots$$

Scaling based on LO description

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Scaling based on LO description

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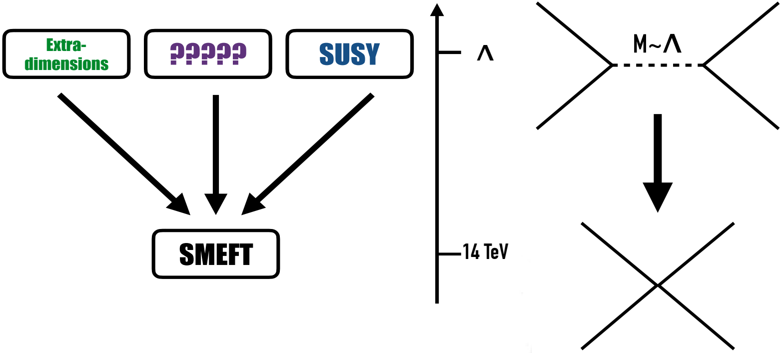
- Complex relation to BSM parameters

Fit parameters $\to$ Model parameter:
precise calculation for each channel, for each model

Model independent BSM constraints

As long as new physics is heavy (no direct production), the SMEFT can encapsulate its effect on LHC physics.



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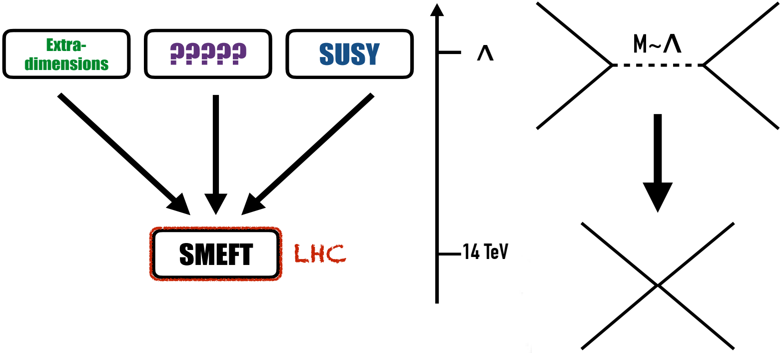

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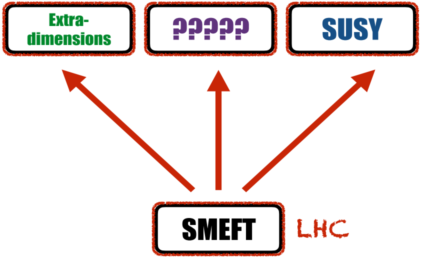

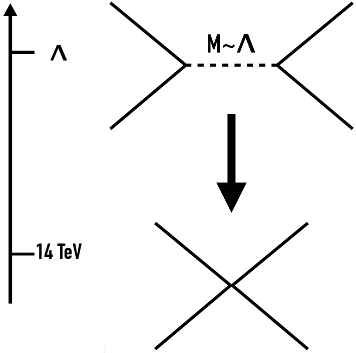

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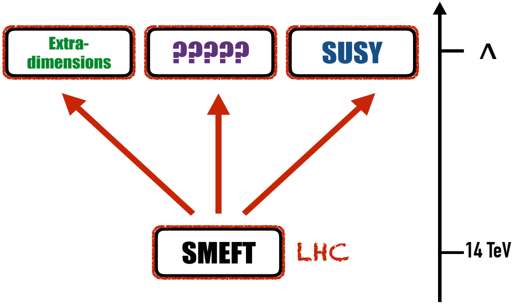
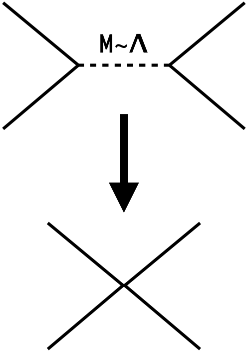




Caveats:

- Standard Model processes (no searches)
- Small deviations: $14\ \mathrm{TeV}/\Lambda \ll 1$

The SMEFT framework

A consistent QFT for parametrizing small BSM effects using higher-dimensional operators with SM fields:

$$\mathcal{L}_{\text{SMEFT}} = \mathcal{L}_{\text{SM}} + \sum_{k=1}^{N} \frac{1}{\Lambda^k} \sum_i C_i \mathcal{O}_i^{[k+4]} \tag{1}$$

Consistent approach to radiative corrections: truncate $\mathcal{L}_{\text{SMEFT}}$ *and* observables at a finite order.

- Dimension 5: 1 operator (neutrino masses)
- Dimension 6: 59 operators

[Weinberg]
[Buchmuller, Wyler]
[Grzadkowski, Iskrzynski, Misiak, Rosiek]

NLO corrections to SMEFT processes

The SMEFT parametrizes possible deviations on precision LHC measurements.
Need for NLO predictions:

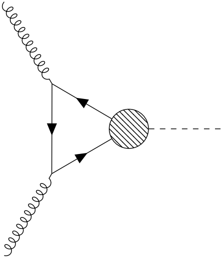
- Better accuracy: SM Higgs cross-section changes by 100% from LO to NLO
- Better precision: reduction of scale uncertainties.
  SMEFT@LO for $gg \to H$: 35% [Maltoni,Vryonidou,Zhang]

Derive stronger and more reliable constraints from global fits.

The top-Higgs sector of the SMEFT

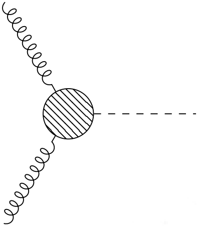
Yukawa correction

$C_1 \bar{Q} \sigma^{\mu\nu} t_R \phi (\phi^\dagger \phi)$



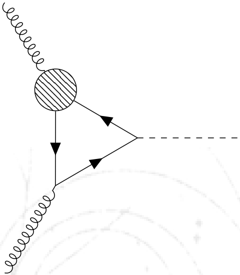
Gluon fusion

$g_s^2 C_2 \phi^\dagger \phi G_{\mu\nu} G^{\mu\nu}$



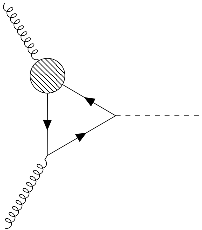
Chromomagnetic

$g_s C_3 \bar{Q} \sigma^{\mu\nu} t_R \phi G_{\mu\nu}$



Light flavors in the loop

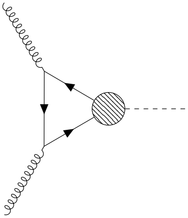
Chromomagnetic operator



Bound on $\frac{C_3^{(f)}}{\Lambda^2} \sim \frac{y_f}{y_t} 1\ \mathrm{TeV}^{-2}$

We can only probe the region where the EFT is not valid

Yukawa modification



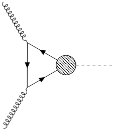
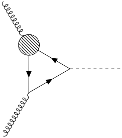
No light-flavor suppression

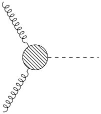
Contributions from light ($\neq b$) quarks bound by direct $q\bar{q} \to H$

Structure of the LO amplitude

Two unusual features:

- Mix of tree-level and one-loop
- UV divergence in loop contribution

$\mathcal{A}^{(0)}_{\text{EFT}} =$ $C_1 \times$  $+ C_3 \times$ 

$+ C_2 \times$ 

[Degrande,Gérard,Grojean,Maltoni,Servant]
[Grazzini,Ilnicka,Spira,Wiesemann]

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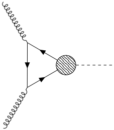
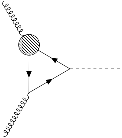


Finite

$+\ C_3 \times$



UV divergent

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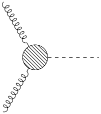

Finite

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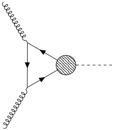
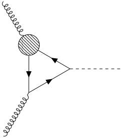
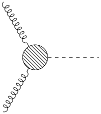
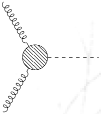
$\mathcal{A}^{(0)}_{\text{EFT}} =$ $C_1 \times$  $+\ C_3 \times$ 

Finite — UV divergent

$+\ C_2 \times$  $+\delta Z_{23} C_3 \times$ 

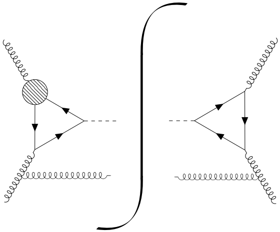
Finite — Counter-term

[Degrande,Gérard,Grojean,Maltoni,Servant]
[Grazzini,Ilnicka,Spira,Wiesemann]

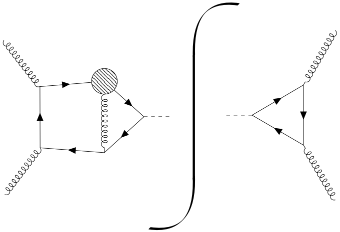
NLO correction to the amplitude

The NLO contribution to the cross-section is composed of

Real emissions



Virtual corrections



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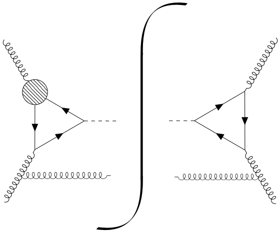
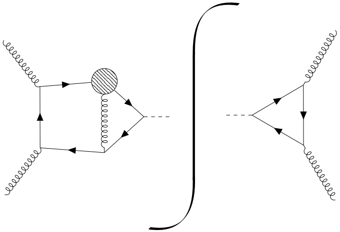


1-loop: automated

Virtual corrections



2-loop: by hand

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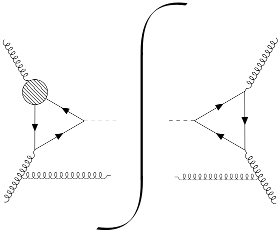

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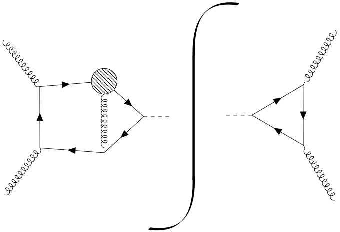


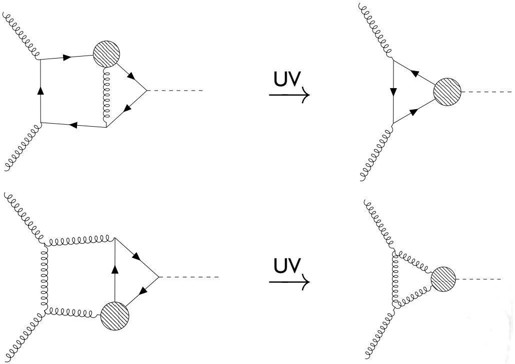
2-loop: by hand

Already considered with resummation for O_1 and O_2 by

[Grazzini,Ilnicka,Spira,Wiesemann]

Divergence structure: operator mixing

The chromomagnetic operator requires counter-terms from both other operators:



Renormalization matrix:
$C_i^0 = Z^{ij} C_j^R$

[Jenkins,Manohar,Trott]

Divergence structure: IR divergences

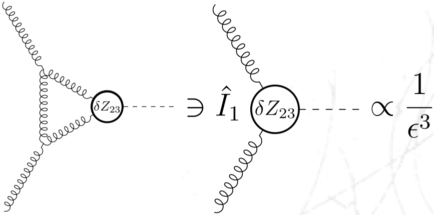
The Infrared divergences factorize:

$$\mathcal{A}_R^{(1)} = \mathcal{A}_{\text{finite}}^{(1)} + \hat{I}_1 \mathcal{A}_R^{(0)}$$

$\hat{I}_1$ is a universal operator encapsulating the IR divergences.

For $gg \to H$, $$\hat{I}_1 = -\frac{e^{\epsilon\gamma}}{\Gamma(1-\epsilon)} \left(\frac{C_A}{\epsilon^2} + \frac{\beta_0}{\epsilon} \right) \left(\frac{\mu^2}{-s} \right)^{\epsilon}$$

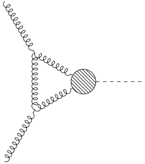
Our LO amplitude already has a pole so an unusual divergence appears :



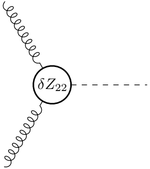
[Catani, Seymour]

Structure of the NLO amplitude

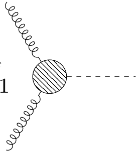
Simplest part of the amplitude: C_2



$$= \mathcal{A}^{(1)}_{\text{finite}}\Big|_{C_2} +$$



$$+ \hat{I}_1$$

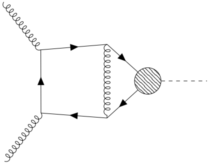


Bare 1-loop — UV divergence — IR divergence

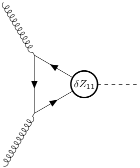
Identical to HEFT calculation

Structure of the NLO amplitude

SM-like two-loop amplitude: C_1



$= \mathcal{A}^{(1)}_{\text{finite}}\Big|_{C_1} +$



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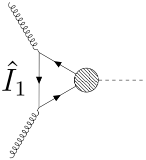

Bare 2-loop — UV divergence — IR divergence

Identical to SM calculation

Structure of the NLO amplitude

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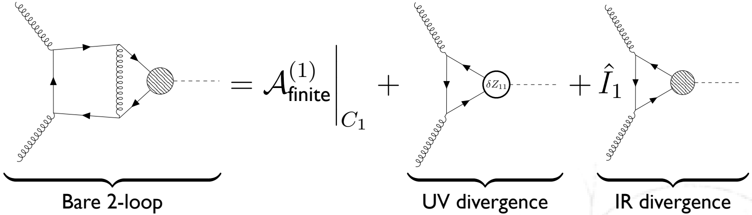
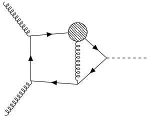


Identical to SM calculation

Structure of the NLO amplitude

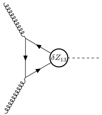
Two-loop and mixing: C_3



$= \mathcal{A}^{(1)}_{\text{finite}}\Big|_{C_1}$

Bare 2-loop

$+$



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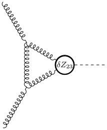

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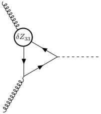
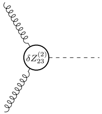
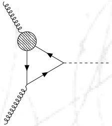


1-loop UV divergences

$+$



$+ \ \hat{I}_1$

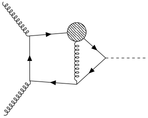


2-loop UV divergence

IR divergence

Structure of the NLO amplitude

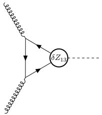
Two-loop and mixing: C_3



$$= \mathcal{A}^{(1)}_{\text{finite}}\Big|_{C_1}$$

Bare 2-loop

$+$



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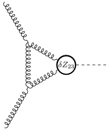

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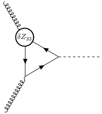

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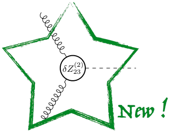

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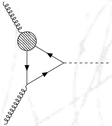
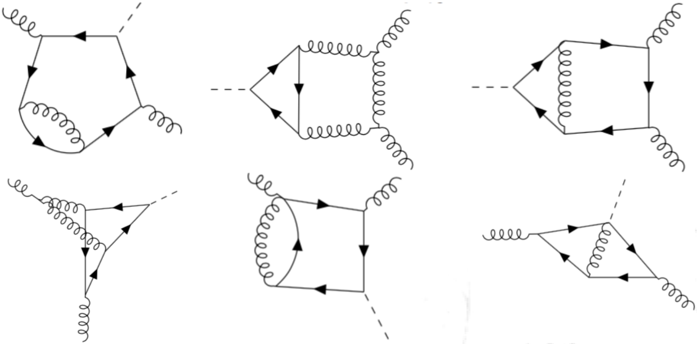


2-loop UV divergence

IR divergence

Our calculation in numbers: diagrams

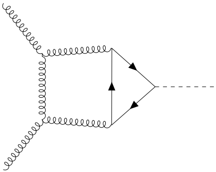
21 diagrams for C_1, 1 for C_2 and 75 for C_3



Our calculation in numbers: integrals and masters

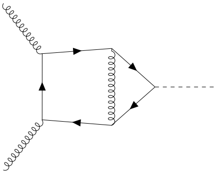
Same integral families as in the SM

Family 1



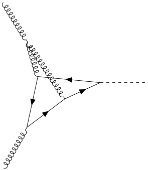
821 Integrals

Family 2



635 Integrals

Family 3



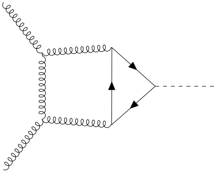
513 Integrals

Total number of master integrals : 17

Our calculation in numbers: integrals and masters

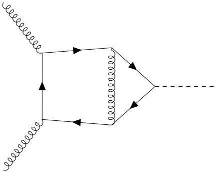
Same integral families as in the SM

Family 1



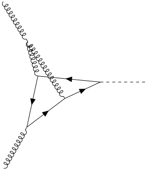
821 Integrals

Family 2



635 Integrals

Family 3



513 Integrals

Total number of master integrals : 17
All known from SM calculation

[Anastasiou, Beerli, Bucherer, Daleo, Kunszt]
[Aglietti, Bonciani, Degrassi, Vicini]

Implementation and checks

- Diagrams generated and evaluated with QGRAF and FORM

  [Nogueira]

  [Kuipers,Ueda,Vermaseren,Vollinga]

- Reduction performed in LiteRed and FIRE5

  [Lee]

  [Smirnov]

- Evaluation with Ginac

  [Bauer,Frink,Kreckel]

- Analytic calculation combined with real emissions in Madgraph5_aMC@NLO

Implementation and checks

Check	SM	O_1	O_2	O_3
LO	✓	✓	✓	✓
NLO	✓	✓	✓	New!

[Mantler, Wiesemann]

[Maltoni, Vryonidou, Zhang]

Cross section at NLO

$$\sigma = \sigma_{\mathsf{SM}} + \frac{(1\ \mathrm{TeV})^2}{\Lambda^2}\left(C_1\sigma_1 + C_2\sigma_2 + C_3\sigma_3\right)$$

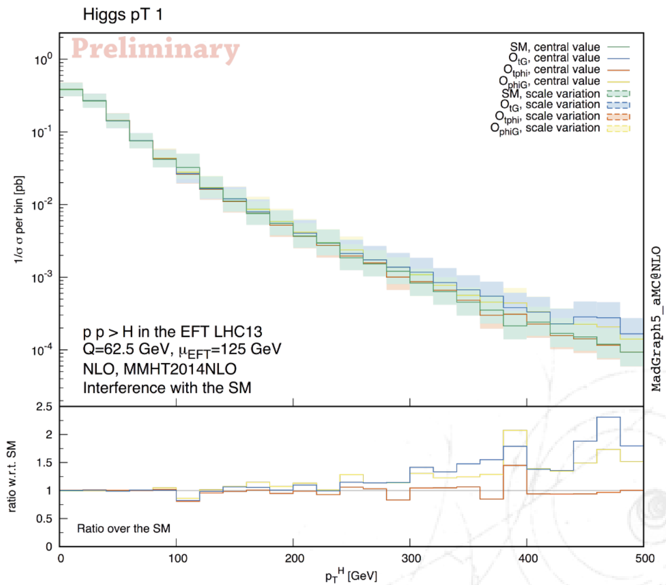
Cross section at NLO

$$\sigma = \sigma_{\mathsf{SM}} + \frac{(1\ \mathrm{TeV})^2}{\Lambda^2}\left(C_1\sigma_1 + C_2\sigma_2 + C_3\sigma_3\right)$$

	σ_1	σ_2	σ_3
LO (pb)	$2.9 \pm 34\%$	$2.6 \times 10^3 \pm 34\%$	27.2 ± 34
NLO (pb)	$4.712 \pm 26\%$	$4.1 \times 10^3 \pm 25\%$	$44.0 \pm 25\%$
K-factor	1.6	1.6	1.6

Preliminary

Higgs transverse momentum



Conclusion and outlook

First complete calculation of the NLO cross section for gluon fusion in the SMEFT with full top mass dependence

- Determined the two-loop renormalization of the chromomagnetic operator
- As in the SM, very large K-factor, universal in the total cross section
- Decrease of the scale dependence as expected

More detailed analysis of the effect of NLO corrections in p_T and rapidity spectra to come in the next few weeks

Thank you for your attention