Introduction to SMEFT and considerations from theory

Darren Scott

University of Amsterdam

Nikhef

Outline

- SMEFT basics
- “Considerations” from theory
- NLO predictions

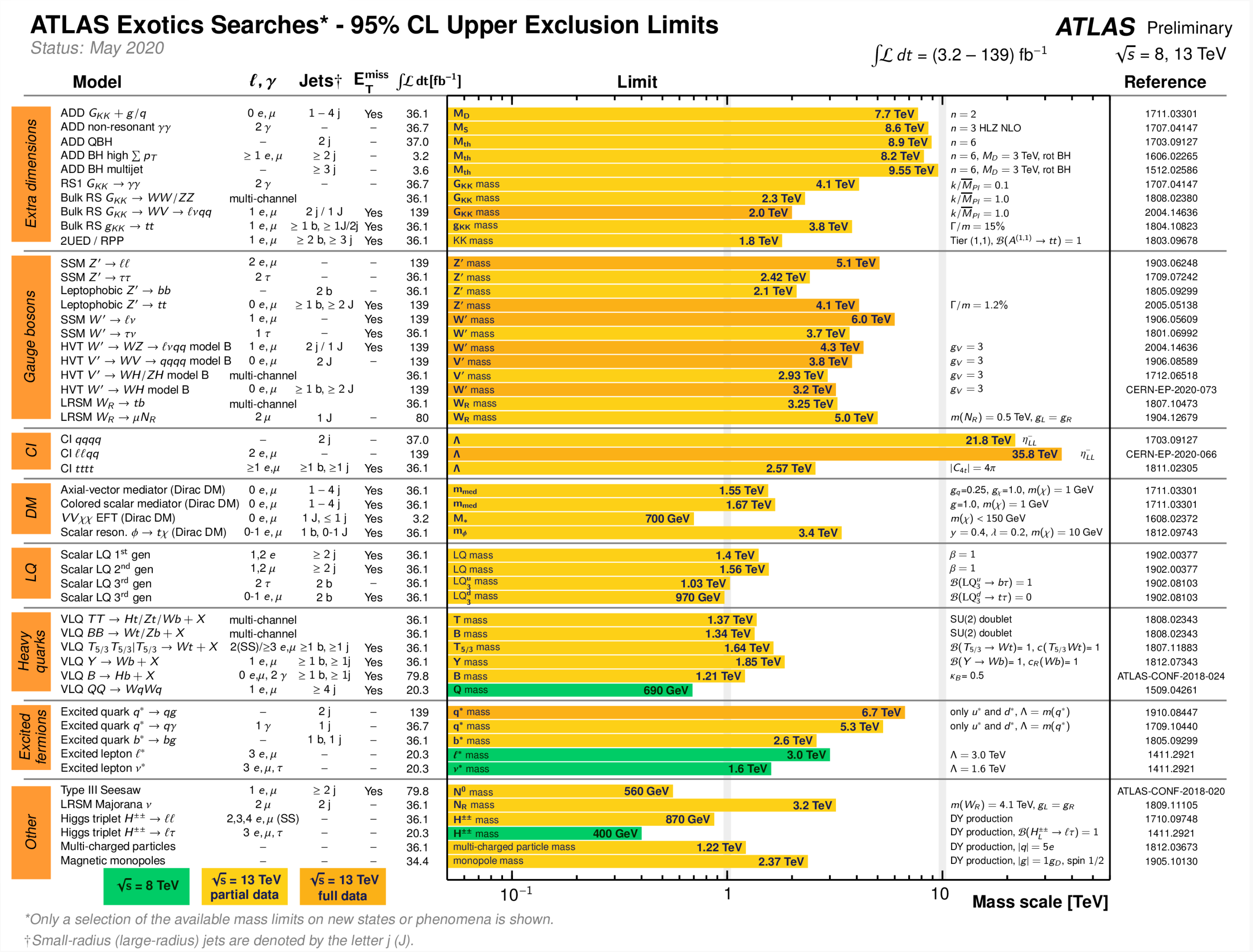
The Standard Model Effective Field Theory: Brief introduction

Motivation

Absence of direct discovery
of new physics at the LHC

Bounds on mass scale associated with new physics pushed much higher

→ Make use of EFT to find deviations



The Standard Model Effective Field Theory: Brief introduction

The idea:

If the new physics is heavy then "integrating it out" leads to higher dimensional operators in the Lagrangian - an EFT.

SMEFT is an EFT extension of the SM.

$$\mathcal{L}_{\rm SMEFT} = \mathcal{L}_{\rm SM} + \mathcal{L}^{(5)} + \mathcal{L}^{(6)} + \mathcal{L}^{(7)} + \ldots$$

$\mathcal{L}^{(d)}$ - contains operators of mass dimension d

The Standard Model Effective Field Theory: Brief introduction

Make predictions with $\mathcal{L}_{\mathrm{SMEFT}}$

E.g. top quark production at The LHC,
Higgs boson decays, ...

$$\text{Prediction} = \begin{array}{c}\text{Prediction}\\ \text{from } \mathcal{L}_{\mathrm{SM}}\end{array} + \sum_i \frac{C_i}{\Lambda_{\mathrm{NP}}^2} f_i(\{p\},\{x\})$$

SM parameters,
kinematics

The Standard Model Effective Field Theory: Brief introduction

Make predictions with $\mathcal{L}_{\mathrm{SMEFT}}$

E.g. top quark production at The LHC,
Higgs boson decays, ...

$$\text{Prediction} = \text{Prediction from } \mathcal{L}_{\mathrm{SM}} + \sum_i \frac{C_i}{\Lambda^2_{\mathrm{NP}}} f_i(\{p\},\{x\})$$

SM parameters, kinematics

Fit to experimental data

The Standard Model Effective Field Theory: Brief introduction

Make predictions with $\mathcal{L}_{\text{SMEFT}}$

E.g. top quar
Higgs boson

New physics shows up as

$$C_i \neq 0$$

Predict

from $\mathcal{L}_{\text{SM}}$

i

Λ_{NP}

$p\}, \{x\})$

SM parameters,
kinematics

Fit to experimental data

The Standard Model Effective Field Theory: Brief introduction

$$\mathcal{L}_{\mathrm{SMEFT}} = \mathcal{L}_{\mathrm{SM}} + \mathcal{L}^{(5)} + \mathcal{L}^{(6)} + \mathcal{L}^{(7)} + \ldots$$

$$\mathcal{L}^{(d)} = \sum_i \frac{C_i^{[d]}}{\Lambda_{\mathrm{NP}}^{d-4}} Q_i^{[d]}$$

Scale of `new physics'

$C_i^{[d]}$ –Wilson coefficient

$Q_i^{[d]}$ – Operator of mass dimension *d*

<u>Rules for operators:</u>
* Built out of only SM fields
* Respect Lorentz and gauge symmetries

<u>Renormalizable?</u>

Yes, if you work to consistent order in Λ_{NP}

The Standard Model Effective Field Theory: Brief introduction

Dimension-5:

$$Q^{[5]} = \left(\overline{\ell^c}\widetilde{H}^*\right)\left(\widetilde{H}^\dagger \ell\right)$$

* Gives rise to neutrino mass

* Expected to be heavily suppressed

Dimension-6:

Rules specified earlier → thousands of operators

Such a basis will be redundant

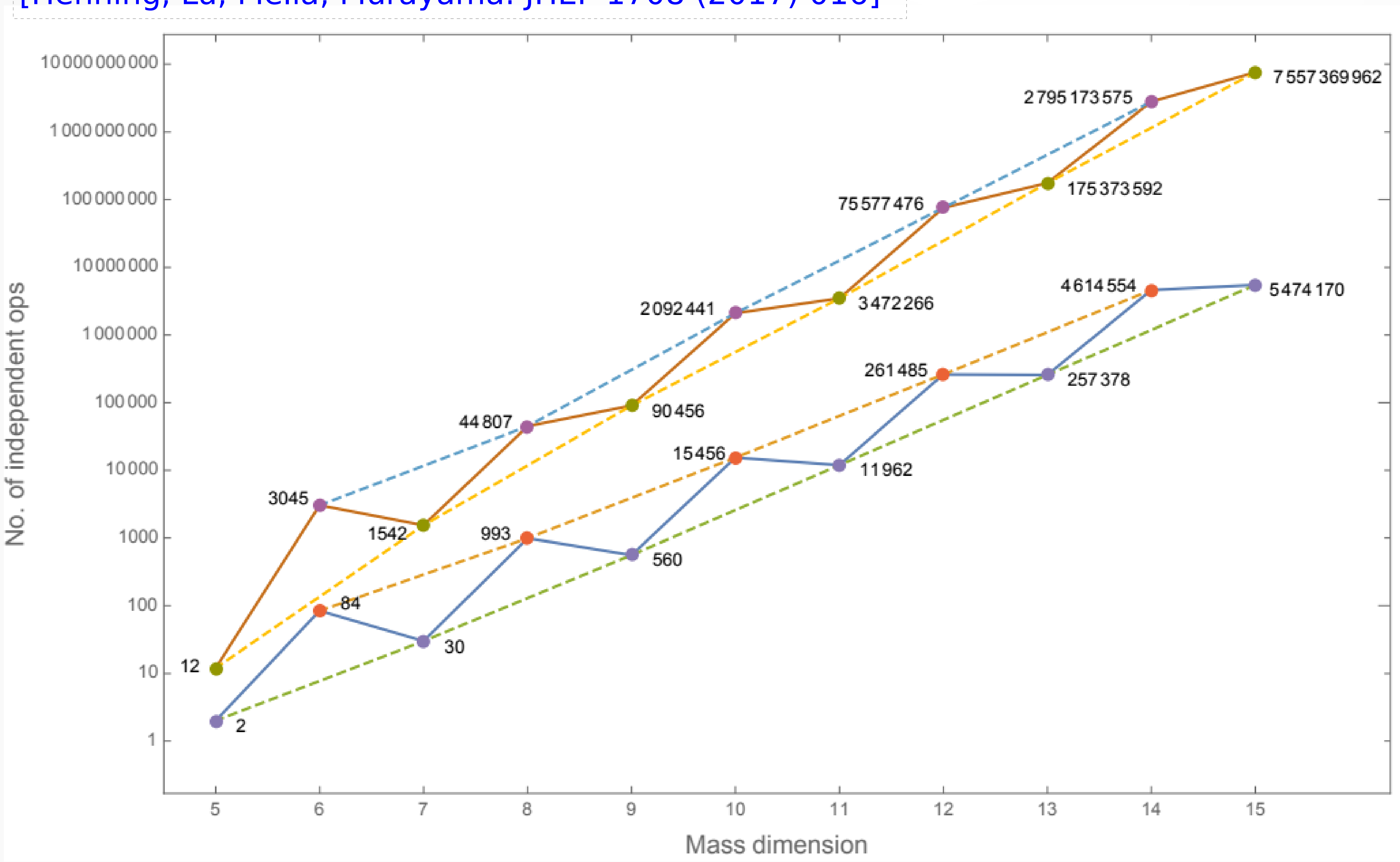
Can use field redefinitions to write some operators as linear combinations of others → Holds even at loop level!

Choose what to remove → basis choice.
Common (and complete) basis is the WARSAW BASIS
[Buchmuller, Wyler: Nucl.Phys. B268 (1986) 621-653]
[Grzadkowski, Iskrzynski, Misiak, Rosiek: JHEP 1010 (2010) 085]

2499 baryon number conserving operators (considering all possible flavour structures!)

The Standard Model Effective Field Theory: Brief introduction

[Henning, Lu, Melia, Murayama: JHEP 1708 (2017) 016]

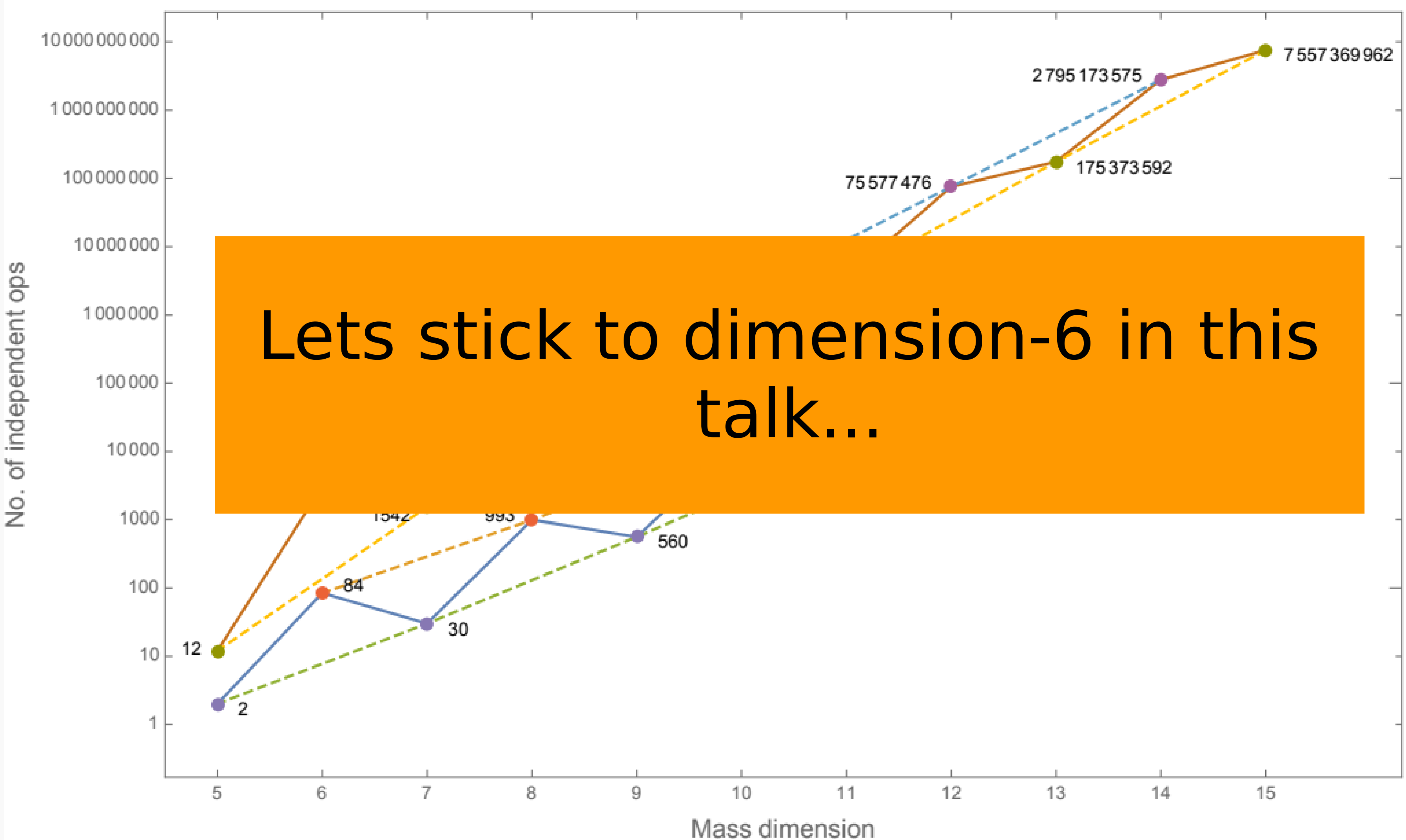


Recently extended up to dim-20

[Marinissen, Rahn, Waalewijn: 2004.09521]

The Standard Model Effective Field Theory: Brief introduction

[Henning, Lu, Melia, Murayama: JHEP 1708 (2017) 016]



Lets stick to dimension-6 in this talk...

Recently extended up to dim-20

[Marinissen, Rahn, Waalewijn: 2004.09521]

The Standard Model Effective Field Theory: Brief introduction

Dimension-6

$1: X^3$	
Q_G	$f^{ABC} G_\mu^{A\nu} G_\nu^{B\rho} G_\rho^{C\mu}$
$Q_{\widetilde{G}}$	$f^{ABC} \widetilde{G}_\mu^{A\nu} G_\nu^{B\rho} G_\rho^{C\mu}$
Q_W	$\epsilon^{IJK} W_\mu^{I\nu} W_\nu^{J\rho} W_\rho^{K\mu}$
$Q_{\widetilde{W}}$	$\epsilon^{IJK} \widetilde{W}_\mu^{I\nu} W_\nu^{J\rho} W_\rho^{K\mu}$

$2: H^6$	
Q_H	$(H^\dagger H)^3$

$3: H^4 D^2$	
$Q_{H\Box}$	$(H^\dagger H)\Box(H^\dagger H)$
Q_{HD}	$\left(H^\dagger D_\mu H\right)^* \left(H^\dagger D_\mu H\right)$

$5: \psi^2 H^3 + \mathrm{h.c.}$	
Q_{eH}	$(H^\dagger H)(\bar{l}_p e_r H)$
Q_{uH}	$(H^\dagger H)(\bar{q}_p u_r \widetilde{H})$
Q_{dH}	$(H^\dagger H)(\bar{q}_p d_r H)$

$4: X^2 H^2$	
Q_{HG}	$H^\dagger H\, G_{\mu\nu}^A G^{A\mu\nu}$
$Q_{H\widetilde{G}}$	$H^\dagger H\, \widetilde{G}_{\mu\nu}^A G^{A\mu\nu}$
Q_{HW}	$H^\dagger H\, W_{\mu\nu}^I W^{I\mu\nu}$
$Q_{H\widetilde{W}}$	$H^\dagger H\, \widetilde{W}_{\mu\nu}^I W^{I\mu\nu}$
Q_{HB}	$H^\dagger H\, B_{\mu\nu} B^{\mu\nu}$
$Q_{H\widetilde{B}}$	$H^\dagger H\, \widetilde{B}_{\mu\nu} B^{\mu\nu}$
Q_{HWB}	$H^\dagger \sigma^I H\, W_{\mu\nu}^I B^{\mu\nu}$
$Q_{H\widetilde{W}B}$	$H^\dagger \sigma^I H\, \widetilde{W}_{\mu\nu}^I B^{\mu\nu}$

$6: \psi^2 X H + \mathrm{h.c.}$	
Q_{eW}	$(\bar{l}_p \sigma^{\mu\nu} e_r)\sigma^I H W_{\mu\nu}^I$
Q_{eB}	$(\bar{l}_p \sigma^{\mu\nu} e_r) H B_{\mu\nu}$
Q_{uG}	$(\bar{q}_p \sigma^{\mu\nu} T^A u_r)\widetilde{H}\, G_{\mu\nu}^A$
Q_{uW}	$(\bar{q}_p \sigma^{\mu\nu} u_r)\sigma^I \widetilde{H}\, W_{\mu\nu}^I$
Q_{uB}	$(\bar{q}_p \sigma^{\mu\nu} u_r)\widetilde{H}\, B_{\mu\nu}$
Q_{dG}	$(\bar{q}_p \sigma^{\mu\nu} T^A d_r) H\, G_{\mu\nu}^A$
Q_{dW}	$(\bar{q}_p \sigma^{\mu\nu} d_r)\sigma^I H\, W_{\mu\nu}^I$
Q_{dB}	$(\bar{q}_p \sigma^{\mu\nu} d_r) H\, B_{\mu\nu}$

$7: \psi^2 H^2 D$	
$Q_{Hl}^{(1)}$	$(H^\dagger i \overleftrightarrow{D}_\mu H)(\bar{l}_p \gamma^\mu l_r)$
$Q_{Hl}^{(3)}$	$(H^\dagger i \overleftrightarrow{D}_\mu^I H)(\bar{l}_p \sigma^I \gamma^\mu l_r)$
Q_{He}	$(H^\dagger i \overleftrightarrow{D}_\mu H)(\bar{e}_p \gamma^\mu e_r)$
$Q_{Hq}^{(1)}$	$(H^\dagger i \overleftrightarrow{D}_\mu H)(\bar{q}_p \gamma^\mu q_r)$
$Q_{Hq}^{(3)}$	$(H^\dagger i \overleftrightarrow{D}_\mu^I H)(\bar{q}_p \sigma^I \gamma^\mu q_r)$
Q_{Hu}	$(H^\dagger i \overleftrightarrow{D}_\mu H)(\bar{u}_p \gamma^\mu u_r)$
Q_{Hd}	$(H^\dagger i \overleftrightarrow{D}_\mu H)(\bar{d}_p \gamma^\mu d_r)$
Q_{Hud} + h.c.	$i(\widetilde{H}^\dagger D_\mu H)(\bar{u}_p \gamma^\mu d_r)$

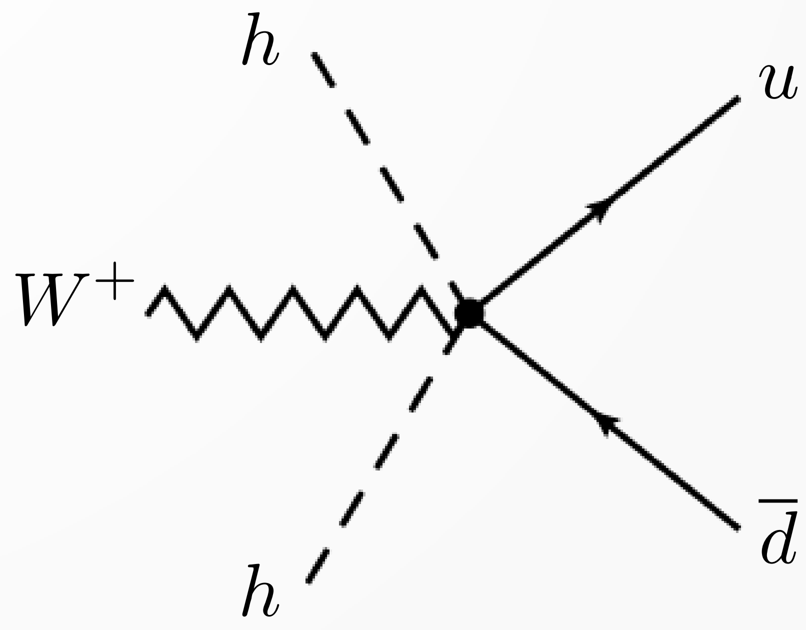
+ 25 distinct 4-fermion operators

The Standard Model Effective Field Theory: Brief introduction

Example interaction:

$7 : \psi^2 H^2 D$	
$Q_{Hl}^{(1)}$	$(H^\dagger i \overleftrightarrow{D}_\mu H)(\bar{l}_p \gamma^\mu l_r)$
$Q_{Hl}^{(3)}$	$(H^\dagger i \overleftrightarrow{D}^I_\mu H)(\bar{l}_p \sigma^I \gamma^\mu l_r)$
Q_{He}	$(H^\dagger i \overleftrightarrow{D}_\mu H)(\bar{e}_p \gamma^\mu e_r)$
$Q_{Hq}^{(1)}$	$(H^\dagger i \overleftrightarrow{D}_\mu H)(\bar{q}_p \gamma^\mu q_r)$
$Q_{Hq}^{(3)}$	$(H^\dagger i \overleftrightarrow{D}^I_\mu H)(\bar{q}_p \sigma^I \gamma^\mu q_r)$
Q_{Hu}	$(H^\dagger i \overleftrightarrow{D}_\mu H)(\bar{u}_p \gamma^\mu u_r)$
Q_{Hd}	$(H^\dagger i \overleftrightarrow{D}_\mu H)(\bar{d}_p \gamma^\mu d_r)$
Q_{Hud} + h.c.	$i(\widetilde{H}^\dagger D_\mu H)(\bar{u}_p \gamma^\mu d_r)$

Can give



Wilson coefficients in processes

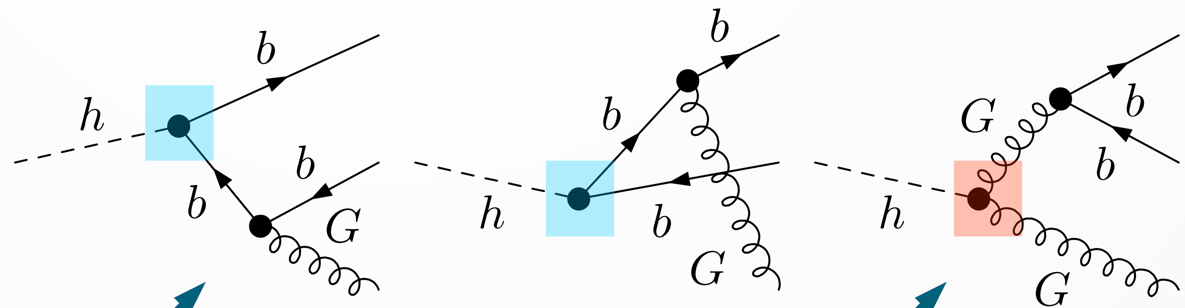
<u>Appearance of Wilson coefficients in a given process</u>

1: **Directly, though new vertex or modification of an old one**

Eg, new vertex:

$C_{HG}(H^\dagger H)G^a_{\mu\nu}G^{a\mu\nu}$

$C_{dH}(H^\dagger H)(\bar{q}Hd)$



Modification of Yukawa-like interactions

Completely new vertex – not in SM

Wilson coefficients in processes

Appearance of Wilson coefficients in a given process

2: **Through through correcting the Higgs kinetic term**

Addition of dim-6 operators ruins cannonical normalization of kinetic terms! E.g.

$$C_{HD}(H^\dagger D_\mu H)^*(H^\dagger D^\mu H) \xrightarrow[\text{EWSB}]{\text{After}} \sim C_{HD}\frac{v^2}{4}(\partial_\mu h)^2$$

To restore canonical normalization, write Higgs doublet as:

$$H(x) = \frac{1}{\sqrt{2}}\begin{pmatrix} -\sqrt{2}i\phi^+(x) \\ \left[1 + C_{H,\text{kin.}}\right]h(x) + i\left[1 - \frac{\hat{v}_T^2}{4}C_{HD}\right]\phi^0(x) + v_T \end{pmatrix}$$

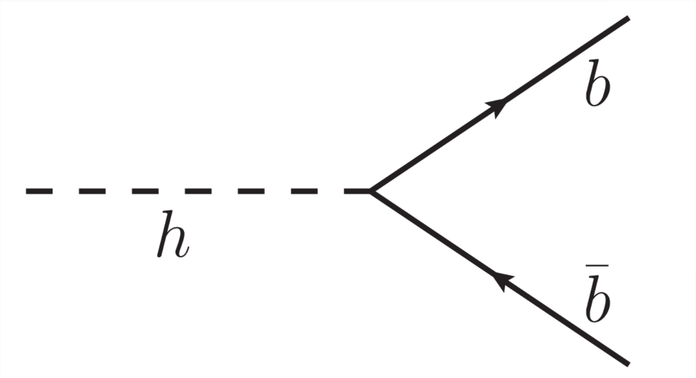
$$C_{H,\text{kin}} \equiv \left(C_{H\Box} - \frac{1}{4}C_{HD}\right)\hat{v}_T^2$$

Wilson coefficients in processes

Appearance of Wilson coefficients in a given process

2: **Through through correcting the Higgs kinetic term**

Implies $C_{HD}, C_{H\Box}$ can show up in any SM like vertex which contains a Higgs field! E.g.



$$\Gamma(h \to b\bar{b}) \sim 2\Gamma_{\mathrm{SM}} C_{H\Box}$$

$$\mathcal{L} \sim C_{H\Box}(H^\dagger H)\Box(H^\dagger H)$$

Wilson coefficients in processes

Appearance of Wilson coefficients in a given process

3: **Relations between parameters**

Not all parameters are independent. Expressing answer in terms of `input’ variables can lead to additional dim-6 contributions.

E.g: $$\cos\theta_w = \frac{M_W}{M_Z}\left(1 + \frac{v^2}{4}C_{HD} + \frac{s_w^2 v^2}{2c_w}C_{HWB}\right)$$

4: **Through running**

Running C_i between scales → full set of operators mix into each other! (E.g. Important for matching)

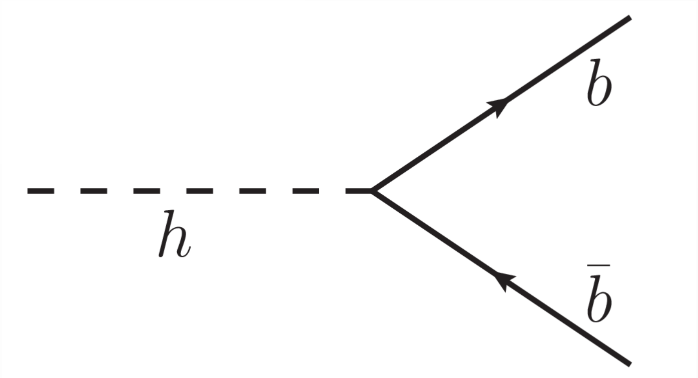
$$\mu\frac{\mathrm{d}C_i}{\mathrm{d}\mu} = \gamma_{ij}C_j$$

Wilson coefficients in processes

Appearance of Wilson coefficients in a given process

Higgs decay example

$$\Gamma^{(4,0)} = \frac{N_c m_H m_b^2}{8\pi \hat{v}_T^2}$$



$$\Gamma^{(6,0)} = 2\Gamma^{(4,0)} \left[C_{H\Box} - \frac{C_{HD}}{4}\left(1 - \frac{\hat{c}_w^2}{\hat{s}_w^2}\right) + \frac{\hat{c}_w}{\hat{s}_w} C_{HWB} - \frac{\hat{v}_T}{m_b}\frac{C_{bH}}{\sqrt{2}}\right] \hat{v}_T^2$$

From redefinition of Higgs doublet

Replacement of VEV by physical parameters

- Explicit operator contribution
- Replacement of Yukawa terms

Narrow width in the SMEFT

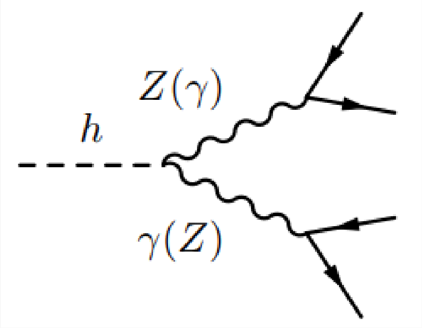
The appearance of new $h\gamma\gamma, hZ\gamma$ tree-level vertices in the SMEFT can lead to problems for the narrow width approximation in $\Gamma(h \to 4f)$

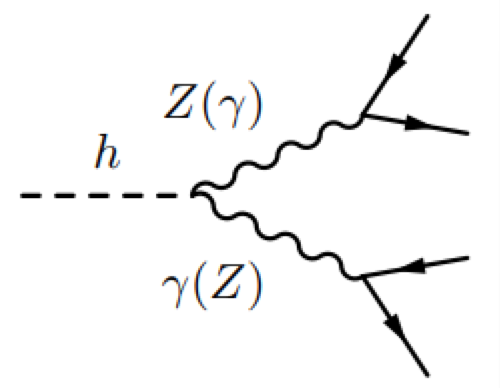
[Brivio, Corbett, Trott: JHEP 10 (2019) 056 (1906.06949)]

Naive use of narrow width approximation misses certain contributions:

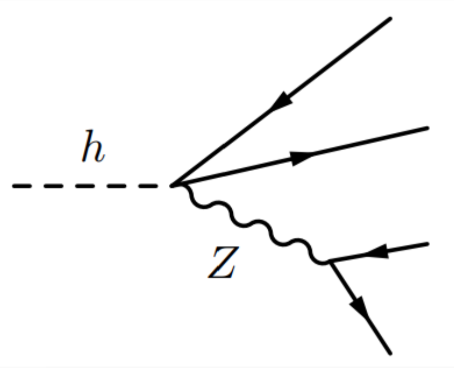
E.g:

Photon mediated diagrams





Contact interactions



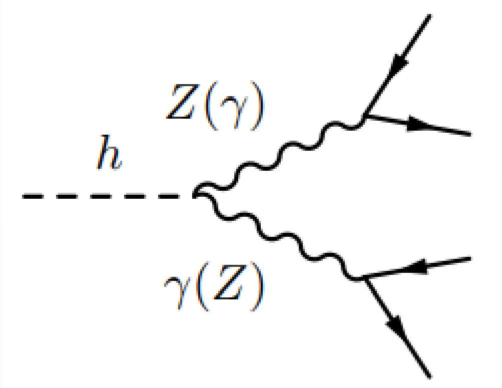
As well as some other effects (interference W and Z mediated)

Narrow width in the SMEFT

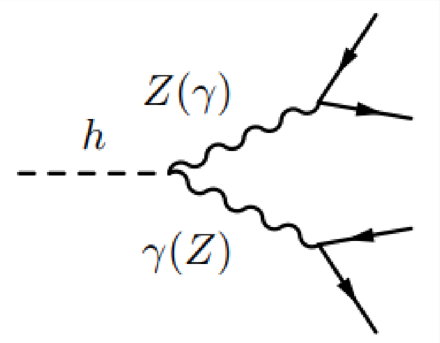
[Brivio, Corbett, Trott: JHEP 10 (2019) 056 (1906.06949)]

Contribution of $h\gamma\gamma, hZ\gamma$ mediated process compared to $WW+ZZ$ contributions

$$\Gamma^{\mathrm{SMEFT}} = \Gamma^{\mathrm{SM}}\left[1+\sum_i a_i C_i\right]$$



Example contributions to a_i from given process



$h \to S$	$\tilde{C}_{HW}$			$\tilde{C}_{HB}$			$\tilde{C}_{HWB}$		
	$Z\gamma$	$\gamma\gamma$	WW, ZZ	$Z\gamma$	$\gamma\gamma$	WW, ZZ	$Z\gamma$	$\gamma\gamma$	WW, ZZ
$\ell_p^+\ell_p^-\ell_r^+\ell_r^-$	**1.04**	-0.009	-0.78	**$-$1.04**	-0.03	-0.22	**$-$0.70**	0.02	0.30
$\ell_p^+\ell_p^-\bar{\nu}_r\nu_r$	0.52		-0.78	**$-$0.52**		-0.22	**$-$0.35**		-0.06
$\bar{u}_p u_p \bar{u}_r u_r$	**2.26**	-0.04	-0.78	**$-$2.26**	-0.15	-0.22	**$-$1.51**	0.08	1.13
$\bar{d}_p d_p \bar{d}_r d_r$	**1.53**	-0.02	-0.78	**$-$1.53**	-0.07	-0.22	**$-$1.02**	0.04	0.63
$\bar{u}_p u_p \bar{d}_r d_r$	**1.89**	-0.03	-0.78	**$-$1.89**	-0.10	-0.22	**$-$1.26**	0.05	0.88
$\ell_p^+\ell_p^-\bar{u}_{p,r}u_{p,r}$	**1.65**	-0.02	-0.78	**$-$1.65**	-0.07	-0.22	**$-$1.10**	0.04	0.71
$\ell_p^+\ell_p^-\bar{d}_{p,r}d_{p,r}$	**1.29**	-0.01	-0.78	**$-$1.29**	-0.05	-0.22	-0.86	0.02	0.46

Input scheme dependence

Input scheme dependence:

Using different input variables changes the numerical coefficients!

[Brivio, Corbett, Trott: JHEP 10 (2019) 056 (1906.06949)]

$\{\alpha, M_Z, G_F, M_H\}$ $$\frac{\Gamma^{\rm SMEFT}_{\rm LO}}{\Gamma^{\rm SM}_{\rm LO}} = 1 + 2.89 C_{HWB} + 0.34 C_{HD} - 1.38 C^{(3)}_{H\ell} + \ldots$$

$\{M_W, M_Z, G_F, M_H\}$ $$\frac{\Gamma^{\rm SMEFT}_{\rm LO}}{\Gamma^{\rm SM}_{\rm LO}} = 1 + 1.21 C_{HWB} - 0.43 C_{HD} - 2.32 C^{(3)}_{H\ell} + \ldots$$

* Predictions should state which scheme (and renormalization scheme) has been used → not well done in literature so far...

* Fits should make use of consistent schemes.

Limitations of SMEFT

The SMEFT does not encompass all possibilities for new physics.
(Even looking beyond dim-6 operators) → Many CP violating effects come into play only later.

1: New physics must be heavy!

$$\frac{v}{\Lambda_{\mathrm{NP}}} \ll 1$$

2: SMEFT assumes Higgs in $SU(2)_L$ doublet.
In some sense, the simplest "broad" extension of the SM.

Gravity: mixing between scalar component of graviton and Higgs
→ Nonlinearities

Broader EFTs available (HEFT)

NLO predictions from SMEFT

NLO predictions often necessary to:
  * Meet required precision
  * Give more meaningful theory uncertainties

Unlike SM, not currently automated in SMEFT.

Structure of higher order corrections still under development somewhat.

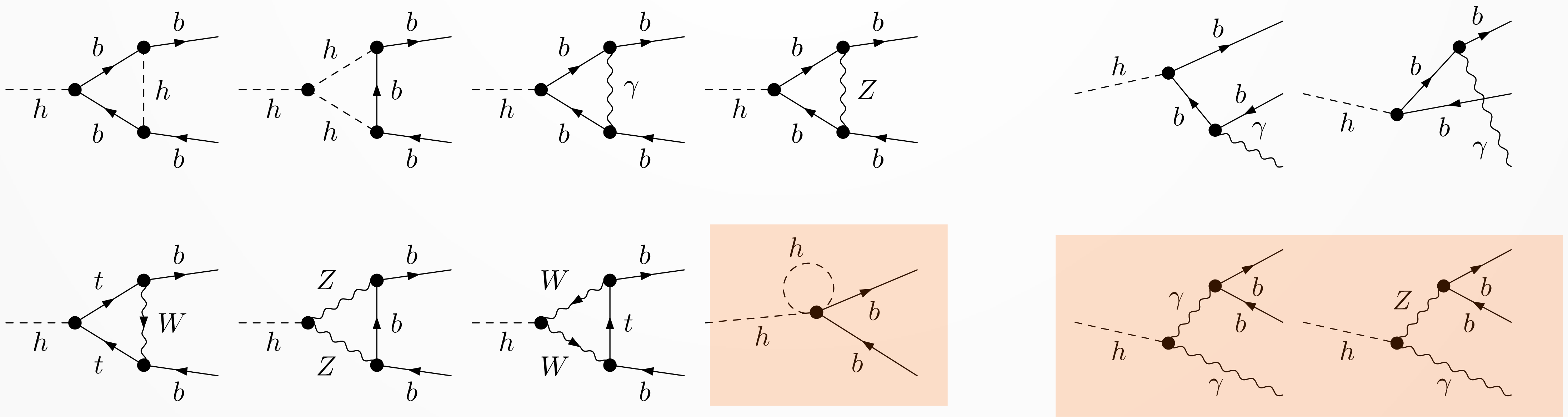
Previously worked on $\Gamma^{\mathrm{SMEFT}}(h \to b\bar{b})$

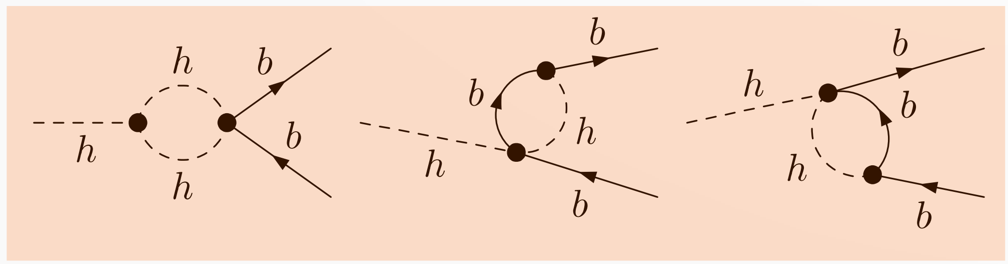
[Gauld, Pecjak, DJS:
JHEP 1605 (2016) 080 &
Phys.Rev. D94 (2016) no.7, 074045]

[Cullen, Pecjak, DJS: JHEP 1908 (2019) 173]

NLO predictions from SMEFT

Sample diagrams/interactions:





$\Longrightarrow$ Don't exist in SM!

NLO predictions from SMEFT

Compute width (inverse lifetime)

Leading Order

$$\Gamma^{(6,0)} = 2\Gamma^{(4,0)} \left[C_{H\Box} - \frac{C_{HD}}{4}\left(1 - \frac{\hat{c}_w^2}{\hat{s}_w^2}\right) + \frac{\hat{c}_w}{\hat{s}_w} C_{HWB} - \frac{\hat{v}_T}{m_b}\frac{C_{bH}}{\sqrt{2}} \right] \hat{v}_T^2$$

Next-to-leading order: $\Gamma^{(6,1)} \sim$ 45 coefficients

Corrections to tree level coefficients:

	SM	C_{HWB}	$C_{H\Box}$	C_{bH}	C_{HD}
NLO QCD-QED	18.2%	17.9%	18.2%	18.2%	18.2%
NLO large-m_t	-3.1%	-4.6%	3.2%	3.5%	-9.0%
NLO remainder	-2.2%	-1.9%	-1.2 %	0.6%	-2.0%
NLO correction	12.9%	11.3%	20.2%	22.3%	7.1%

NLO predictions from SMEFT

Compute width (inverse lifetime)

Leading Order

$$\Gamma^{(6,0)} = 2\Gamma^{(4,0)} \left[C_{H\Box} - \frac{C_{HD}}{4}\left(1 - \frac{\hat{c}_w^2}{\hat{s}_w^2}\right) + \frac{\hat{c}_w}{\hat{s}_w} C_{HWB} - \frac{\hat{v}_T}{m_b}\frac{C_{bH}}{\sqrt{2}}\right] \hat{v}_T^2$$

Next-to-leading order: $\Gamma^{(6,1)} \sim$ 45 coefficients

New C_i can appear from loop diagrams with large coefficients

NLO SMEFT calculations have important implications for fitting!

Summary

* Basics of what the SMEFT is

* Origin of couplings in processes

* Use of narrow width in SMEFT not automatic

* Input scheme dependence important when fitting

* NLO predictions can be important

Summary

* Basics of what the SMEFT is

* Origin of couplings in processes

* Use of narrow width in SMEFT not automatic

* Input scheme dependence important when fitting

* NLO predictions can be important

Thank you for your attention