(Some of the)

Recent developments in SMEFT theory, tools and phenomenology

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MTTD

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Why Effective Field Theories?

- We need BSM physics
  (dark matter, dark energy, matter-antimatter asymmetry, …)

- No BSM particles discovered so far → $\Lambda_{BSM} \gg M_W\,?$

- We can use the Effective Field Theory framework
  heavy BSM particles have indirect impact on known interactions

- EFT Lagrangian can be consistently defined as an expansion in $1/\Lambda$

$$\mathscr{L}_{\mathrm{EFT}} = \mathscr{L}_{\mathrm{SM}} + \frac{1}{\Lambda}\mathscr{L}_5 + \frac{1}{\Lambda^2}\mathscr{L}_6 + \dots$$

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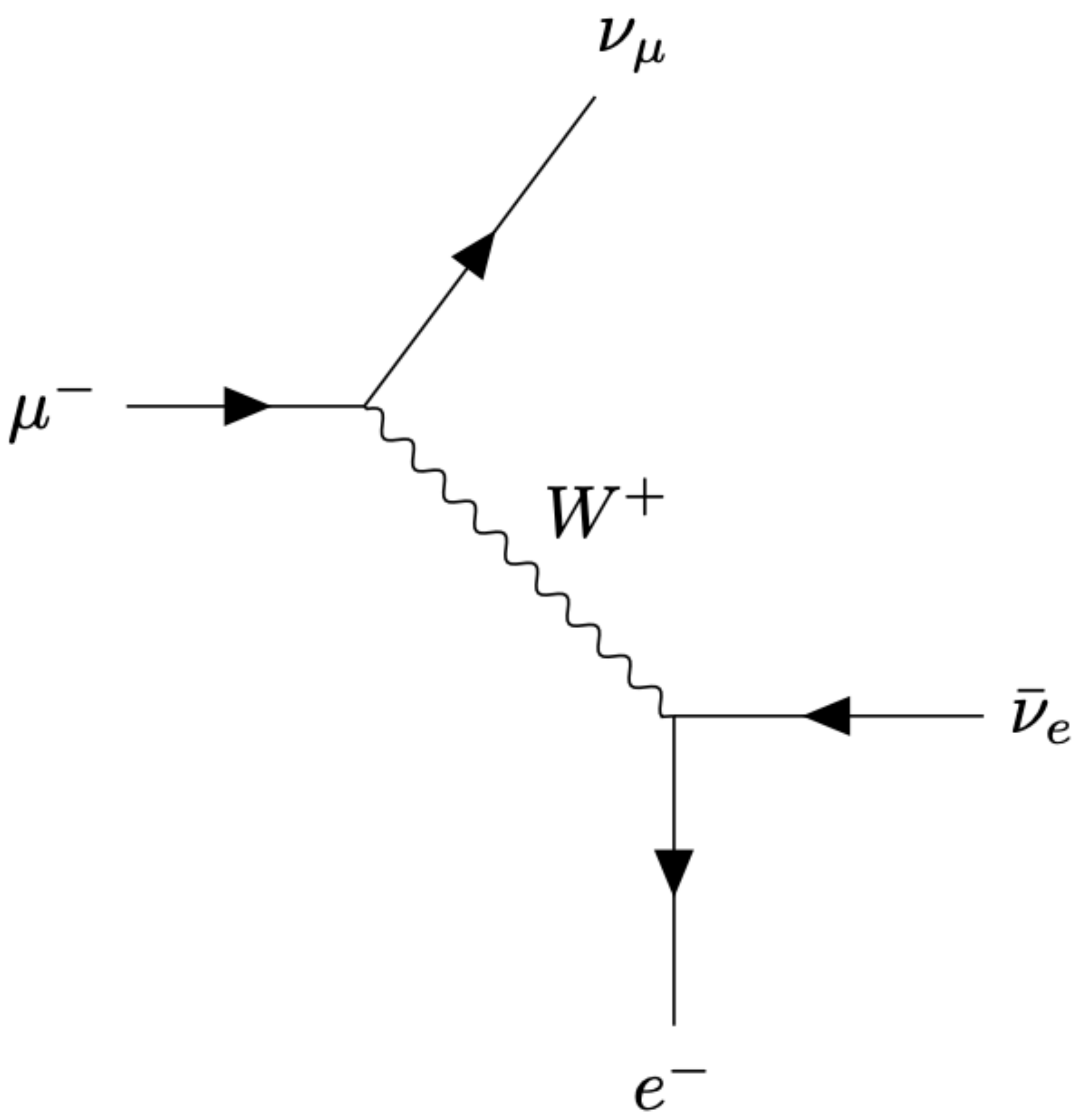
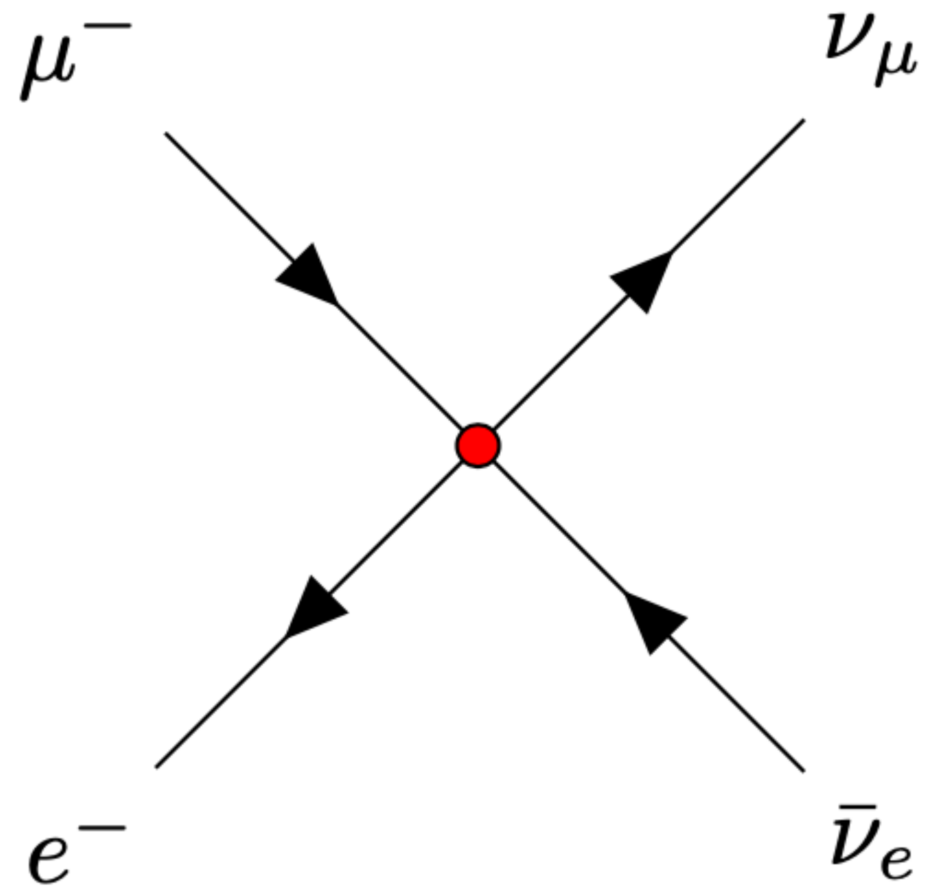
Following Fermi's footsteps





$$\mathscr{M}_{EW} \propto \frac{g^2}{2} \frac{1}{p_W^2 - M_W^2} \qquad M_W \gg p_W \qquad \mathscr{M}_{Fermi} \propto G_F = \frac{\sqrt{2} g^2}{8 M_W^2}$$

$$G_F \approx 1.1664 \times 10^{-5}\ \text{GeV}^{-2} = \frac{1}{\Lambda_{EW}^2} \qquad \Lambda_{EW} \approx 290\ \text{GeV}$$

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EFTs for BSM physics

SMEFT
Standard Model Effective Field Theory

$$\mathscr{L}_{\text{SMEFT}} = \mathscr{L}_{\text{SM}} + \sum_i \frac{C_i Q_i}{\Lambda^{d_i - 4}}$$

- C_i - dimensionless Wilson coefficients
- Q_i - higher dimensional effective operators of dimension d_i
- Λ - New Physics Scale - power counting
- SM gauge symmetry $SU(3)_C \times SU(2)_L \times U(1)_Y$
- Higgs - part of SU(2) doublet

$$\varphi = \begin{pmatrix} \Phi^+ \\ \frac{1}{\sqrt{2}}\left(v + H + i\Phi^0\right) \end{pmatrix}$$

- Suited for heavy UV completions
- Review e.g. G. Isidori et al. 2303.16922

HEFT
Higgs Effective Field Theory

$$\mathscr{L}_{\text{HEFT}} = \mathscr{L}_{LO} + \mathscr{L}_{NLO} + \mathscr{L}_{NNLO} + \mathscr{L}_{NNNLO} + \ldots$$

- Higgs *h* - SU(2) singlet
- Goldstone Bosons treated separately: $\mathrm{U} = \exp\left(\frac{i\,\vec{\sigma}\cdot\vec{\pi}}{v}\right)$
- More complicated power counting
- More general than SMEFT but less predictive (more free parameters)
- Suited to study e.g. Composite Higgs models
- Review e.g. I. Brivio et al. 1604.06801

EFTs for BSM physics

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HEFT
Higgs Effective Field Theory

$$\mathscr{L}_{\mathrm{HEFT}} = \mathscr{L}_{LO} + \mathscr{L}_{NLO} + \mathscr{L}_{NNLO} + \mathscr{L}_{NNNLO} + \ldots$$

- Higgs *h* - SU(2) singlet
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- More general than SMEFT but less predictive (more free parameters)
- Suited to study e.g. Composite Higgs models
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This talk more focused on SMEFT

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(Some) key aspects of SMEFT and EFTs

This talk:

- **Operator bases & higher dimensions**

- **Phenomenology**
  - Precision #1 - loops & RG evolution
  - Precision #2 - higher orders in the EFT expansion
  - Fits & matching to UV completions

- **On-shell methods**

Many other topics, such as:

- **Geometric interpretations**
  A. Helset et al. 2001.01453

- **EFT validity & unitarity**
  A. Cappati et al. 2205.15959 L. Bresciani et al. 2504.12855 G. N. Remmen, N. L. Rodd 2412.07827

(Some) key aspects of SMEFT and EFTs

- Operator bases & higher dimensions
- Phenomenology
  - Precision #1 - loops & RG evolution
  - Precision #2 - higher orders in the EFT expansion
  - Fits & matching to UV completions
- On-shell methods

SMEFT operator bases

- **Dimension-6**
  Warsaw basis B. Grządkowski et al. 1008.4884

- **Dimension-7 (odd dimension, fermionic, LNV & BNV)**
  L. Lehman 1410.4193

- **Dimension-8**
  C. Murphy 2005.00059 H. Li et al. 2005.00008

- **Dimension-9**
  Y. Liaoa and X. Ma 2007.08125

- **Dimension-10, 11, 12**
  R.V. Harlander et al. 2305.06832

d_i	$n_f = 1$	$n_f = 3$
5	2	12
6	84	3045
8	993	44807
10	15456	2092441

Number of operators of mass dimension d_i and number of fermion generations n_f

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SMEFT operator bases

- **Dimension-6**
  Warsaw basis B. Grządkowski et al. 1008.4884

- **Dimension-8**
  C. Murphy 2005.00059 H. Li et al. 2005.00008

Relevant for phenomenology

d_i	$n_f = 1$	$n_f = 3$
5	2	12
6	84	3045
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Number of operators of mass dimension d_i and number of fermion generations n_f

Dim-6 SMEFT Warsaw basis

B. Grządkowski, M. Iskrzyński, M. Misiak, J. Rosiek 1008.4884

- **Minimal basis of independent operators**
- **Constructed in unbroken phase before SSB**
- **Contains 59+1 independent operators (84+2 when we CC counted separately)**
- **Aims at minimising the number of derivatives**

Dim-6 SMEFT Warsaw basis

59 independent dimension-6 operators

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	$\epsilon^{IJK} W_\mu^{I\nu} W_\nu^{J\rho} W_\rho^{K\mu}$	$Q_{\varphi D}$	$\left(\varphi^\dagger D^\mu\varphi\right)^* \left(\varphi^\dagger D_\mu\varphi\right)$	$Q_{d\varphi}$	$(\varphi^\dagger\varphi)(\bar q_p d_r \varphi)$
$Q_{\widetilde W}$	$\epsilon^{IJK} \widetilde W_\mu^{I\nu} W_\nu^{J\rho} W_\rho^{K\mu}$				

$X^2\varphi^2$		$\psi^2 X\varphi$		$\psi^2\varphi^2 D$	
$Q_{\varphi G}$	$\varphi^\dagger\varphi\, G^A_{\mu\nu} G^{A\mu\nu}$	Q_{eW}	$(\bar l_p \sigma^{\mu\nu} e_r)\tau^I \varphi W^I_{\mu\nu}$	$Q_{\varphi l}^{(1)}$	$i(\varphi^\dagger \overleftrightarrow{D}_\mu \varphi)(\bar l_p \gamma^\mu l_r)$
$Q_{\varphi\widetilde G}$	$\varphi^\dagger\varphi\, \widetilde G^A_{\mu\nu} G^{A\mu\nu}$	Q_{eB}	$(\bar l_p \sigma^{\mu\nu} e_r)\varphi B_{\mu\nu}$	$Q_{\varphi l}^{(3)}$	$i(\varphi^\dagger \overleftrightarrow{D}^I_\mu \varphi)(\bar l_p \tau^I \gamma^\mu l_r)$
$Q_{\varphi W}$	$\varphi^\dagger\varphi\, W^I_{\mu\nu} W^{I\mu\nu}$	Q_{uG}	$(\bar q_p \sigma^{\mu\nu} T^A u_r)\widetilde\varphi\, G^A_{\mu\nu}$	$Q_{\varphi e}$	$i(\varphi^\dagger \overleftrightarrow{D}_\mu \varphi)(\bar e_p \gamma^\mu e_r)$
$Q_{\varphi\widetilde W}$	$\varphi^\dagger\varphi\, \widetilde W^I_{\mu\nu} W^{I\mu\nu}$	Q_{uW}	$(\bar q_p \sigma^{\mu\nu} u_r)\tau^I \widetilde\varphi\, W^I_{\mu\nu}$	$Q_{\varphi q}^{(1)}$	$i(\varphi^\dagger \overleftrightarrow{D}_\mu \varphi)(\bar q_p \gamma^\mu q_r)$
$Q_{\varphi B}$	$\varphi^\dagger\varphi\, B_{\mu\nu} B^{\mu\nu}$	Q_{uB}	$(\bar q_p \sigma^{\mu\nu} u_r)\widetilde\varphi\, B_{\mu\nu}$	$Q_{\varphi q}^{(3)}$	$i(\varphi^\dagger \overleftrightarrow{D}^I_\mu \varphi)(\bar q_p \tau^I \gamma^\mu q_r)$
$Q_{\varphi\widetilde B}$	$\varphi^\dagger\varphi\, \widetilde B_{\mu\nu} B^{\mu\nu}$	Q_{dG}	$(\bar q_p \sigma^{\mu\nu} T^A d_r)\varphi\, G^A_{\mu\nu}$	$Q_{\varphi u}$	$i(\varphi^\dagger \overleftrightarrow{D}_\mu \varphi)(\bar u_p \gamma^\mu u_r)$
$Q_{\varphi WB}$	$\varphi^\dagger\tau^I\varphi\, W^I_{\mu\nu} B^{\mu\nu}$	Q_{dW}	$(\bar q_p \sigma^{\mu\nu} d_r)\tau^I \varphi\, W^I_{\mu\nu}$	$Q_{\varphi d}$	$i(\varphi^\dagger \overleftrightarrow{D}_\mu \varphi)(\bar d_p \gamma^\mu d_r)$
$Q_{\varphi\widetilde WB}$	$\varphi^\dagger\tau^I\varphi\, \widetilde W^I_{\mu\nu} B^{\mu\nu}$	Q_{dB}	$(\bar q_p \sigma^{\mu\nu} d_r)\varphi\, B_{\mu\nu}$	$Q_{\varphi ud}$	$i(\widetilde\varphi^\dagger D_\mu \varphi)(\bar u_p \gamma^\mu d_r)$

$(\bar LL)(\bar LL)$		$(\bar RR)(\bar RR)$		$(\bar LL)(\bar RR)$	
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}	$(\bar e_p \gamma_\mu e_r)(\bar d_s \gamma^\mu d_t)$	$Q_{qu}^{(1)}$	$(\bar q_p \gamma_\mu q_r)(\bar u_s \gamma^\mu u_t)$
		$Q_{ud}^{(1)}$	$(\bar u_p \gamma_\mu u_r)(\bar d_s \gamma^\mu d_t)$	$Q_{qu}^{(8)}$	$(\bar q_p \gamma_\mu T^A q_r)(\bar u_s \gamma^\mu T^A u_t)$
		$Q_{ud}^{(8)}$	$(\bar u_p \gamma_\mu T^A u_r)(\bar d_s \gamma^\mu T^A d_t)$	$Q_{qd}^{(1)}$	$(\bar q_p \gamma_\mu q_r)(\bar d_s \gamma^\mu d_t)$
				$Q_{qd}^{(8)}$	$(\bar q_p \gamma_\mu T^A q_r)(\bar d_s \gamma^\mu T^A d_t)$

$(\bar LR)(\bar RL)$ and $(\bar LR)(\bar LR)$		B-violating	
Q_{ledq}	$(\bar l_p^j e_r)(\bar d_s q_t^j)$	Q_{duq}	$\epsilon^{\alpha\beta\gamma}\epsilon_{jk}\left[(d_p^\alpha)^T C u_r^\beta\right]\left[(q_s^{\gamma j})^T C l_t^k\right]$
$Q_{quqd}^{(1)}$	$(\bar q_p^j u_r)\epsilon_{jk}(\bar q_s^k d_t)$	Q_{qqu}	$\epsilon^{\alpha\beta\gamma}\epsilon_{jk}\left[(q_p^{\alpha j})^T C q_r^{\beta k}\right]\left[(u_s^\gamma)^T C e_t\right]$
$Q_{quqd}^{(8)}$	$(\bar q_p^j T^A u_r)\epsilon_{jk}(\bar q_s^k T^A d_t)$	Q_{qqq}	$\epsilon^{\alpha\beta\gamma}\epsilon_{jn}\epsilon_{km}\left[(q_p^{\alpha j})^T C q_r^{\beta k}\right]\left[(q_s^{\gamma m})^T C l_t^n\right]$
$Q_{lequ}^{(1)}$	$(\bar l_p^j e_r)\epsilon_{jk}(\bar q_s^k u_t)$	Q_{duu}	$\epsilon^{\alpha\beta\gamma}\left[(d_p^\alpha)^T C u_r^\beta\right]\left[(u_s^\gamma)^T C e_t\right]$
$Q_{lequ}^{(3)}$	$(\bar l_p^j \sigma_{\mu\nu} e_r)\epsilon_{jk}(\bar q_s^k \sigma^{\mu\nu} u_t)$		

Single dimension-5 L-violating operator

$$Q_{\nu\nu} = \varepsilon_{jk}\varepsilon_{mn}\varphi^j\varphi^m (l_p^k)^T C l_r^n \;\equiv\; (\widetilde\varphi^\dagger l_p)^T C (\widetilde\varphi^\dagger l_r)$$

Dim-8 SMEFT basis

C. Murphy 2005.00059 H. Li et al. 2005.00008

Similar logic as behind the Warsaw basis

φ^8		$\varphi^6 D^2$		$\varphi^4 D^4$	
Q_{φ^8}	$(\varphi^\dagger\varphi)^4$	$Q_{\varphi^6\Box}$	$(\varphi^\dagger\varphi)^2\Box(\varphi^\dagger\varphi)$	$Q^{(1)}_{\varphi^4 D^4}$	$(D_\mu\varphi^\dagger D_\nu\varphi)(D^\nu\varphi^\dagger D^\mu\varphi)$
		$Q_{\varphi^6 D^2}$	$(\varphi^\dagger\varphi)(\varphi^\dagger D_\mu\varphi)^*(\varphi^\dagger D^\mu\varphi)$	$Q^{(2)}_{\varphi^4 D^4}$	$(D_\mu\varphi^\dagger D_\nu\varphi)(D^\mu\varphi^\dagger D^\nu\varphi)$
				$Q^{(3)}_{\varphi^4 D^4}$	$(D_\mu\varphi^\dagger D^\mu\varphi)(D_\nu\varphi^\dagger D^\nu\varphi)$

$X^3\varphi^2$		$X^2\varphi^4$	
$Q^{(1)}_{G^3\varphi^2}$	$f^{ABC}(\varphi^\dagger\varphi)G^{A\nu}_\mu G^{B\rho}_\nu G^{C\mu}_\rho$	$Q^{(1)}_{G^2\varphi^4}$	$(\varphi^\dagger\varphi)^2 G^A_{\mu\nu}G^{A\mu\nu}$
$Q^{(2)}_{G^3\varphi^2}$	$f^{ABC}(\varphi^\dagger\varphi)G^{A\nu}_\mu G^{B\rho}_\nu \widetilde{G}^{C\mu}_\rho$	$Q^{(2)}_{G^2\varphi^4}$	$(\varphi^\dagger\varphi)^2 \widetilde{G}^A_{\mu\nu}G^{A\mu\nu}$
$Q^{(1)}_{W^3\varphi^2}$	$\epsilon^{IJK}(\varphi^\dagger\varphi)W^{I\nu}_\mu W^{J\rho}_\nu W^{K\mu}_\rho$	$Q^{(1)}_{W^2\varphi^4}$	$(\varphi^\dagger\varphi)^2 W^I_{\mu\nu}W^{I\mu\nu}$
$Q^{(2)}_{W^3\varphi^2}$	$\epsilon^{IJK}(\varphi^\dagger\varphi)W^{I\nu}_\mu W^{J\rho}_\nu \widetilde{W}^{K\mu}_\rho$	$Q^{(2)}_{W^2\varphi^4}$	$(\varphi^\dagger\varphi)^2 \widetilde{W}^I_{\mu\nu}W^{I\mu\nu}$
$Q^{(1)}_{W^2B\varphi^2}$	$\epsilon^{IJK}(\varphi^\dagger\tau^I\varphi)B^\nu_\mu W^{J\rho}_\nu W^{K\mu}_\rho$	$Q^{(3)}_{W^2\varphi^4}$	$(\varphi^\dagger\tau^I\varphi)(\varphi^\dagger\tau^J\varphi)W^I_{\mu\nu}W^{J\mu\nu}$
$Q^{(2)}_{W^2B\varphi^2}$	$\epsilon^{IJK}(\varphi^\dagger\tau^I\varphi)(\widetilde{B}^{\mu\nu}W^J_{\nu\rho}W^{K\rho}_\mu + B^{\mu\nu}W^J_{\nu\rho}\widetilde{W}^{K\rho}_\mu)$	$Q^{(4)}_{W^2\varphi^4}$	$(\varphi^\dagger\tau^I\varphi)(\varphi^\dagger\tau^J\varphi)\widetilde{W}^I_{\mu\nu}W^{J\mu\nu}$
		$Q^{(1)}_{WB\varphi^4}$	$(\varphi^\dagger\varphi)(\varphi^\dagger\tau^I\varphi)W^I_{\mu\nu}B^{\mu\nu}$
		$Q^{(2)}_{WB\varphi^4}$	$(\varphi^\dagger\varphi)(\varphi^\dagger\tau^I\varphi)\widetilde{W}^I_{\mu\nu}B^{\mu\nu}$
		$Q^{(1)}_{B^2\varphi^4}$	$(\varphi^\dagger\varphi)^2 B_{\mu\nu}B^{\mu\nu}$
		$Q^{(2)}_{B^2\varphi^4}$	$(\varphi^\dagger\varphi)^2 \widetilde{B}_{\mu\nu}B^{\mu\nu}$

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(Some) key aspects of SMEFT and EFTs

- Operator bases & higher dimensions
- Phenomenology
  - Precision #1 - loops & RG evolution
  - Precision #2 - higher orders in the EFT expansion
  - Fits & matching to UV completions
- On-shell methods

SMEFT Pipeline

Calculate precise* predictions for various HEP processes

*in perturbation theory and EFT expansion

Compare with available experimental data to constraint SMEFT WCs

Interpret patterns of WCs using results of matching to UV completions

Obtain insights into the underlying UV model

SMEFT & phenomenology

- Calculations in SMEFT can be very challenging
  - Large number of higher-dimensional operators
  - Complicated flavour structure
  - Precision requires a) higher-order loops b) higher order terms in the EFT expansion

Need for a certain degree of automation!

- Some of the numerical tools
  - SMEFT@NLO C. Degrande et al. 2008.11743
    MC simulations, dim-6 SMEFT, one-loop QCD corrections, massless light fermions
  - SMEFTsim I. Brivio et al. 1709.06492
    MC simulations, dim-6 SMEFT, different flavour assumptions, used for global fits
  - Dim6top J. A. Aguilar Saavedra et al. 1802.07237
    MC simulations, dim-6 SMEFT for top-quark sector, massless light fermions
  - SmeftFR A. Dedes et al. 1904.03204 A. Dedes et al. 2302.01353
    MC simulations, analytical calculations, dim-6 SMEFT, dim-8 bosoninc SMEFT

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SMEFT & phenomenology

Going beyond the tree-level

- **Numerous processes studied**
  @1-loop $Vt\bar{t}$ T. Martini, M. Schulze 1911.11244 $H\gamma\gamma$ A. Dedes et al. 1805.00302
  $Hb\bar{b}$ J. M. Cullen et al. 1904.06358
  @2-loops ggH N. Deutschmann et al. 1708.00460 L. Alasfar et al. 2202.02333,
  $ggHH$ G. Heinrich et al. 2204.13045

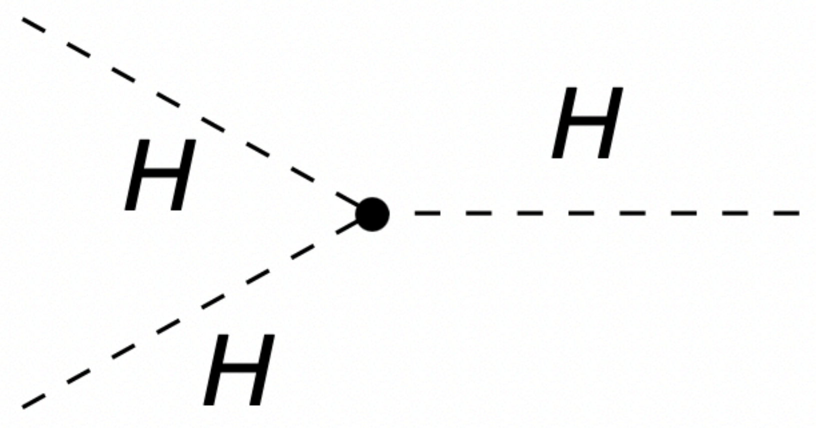
- **RGEs**
  @1-loop in SMEFT a) full result E. Jenkins 1308.2627 **b) tools: DsixTools** J. Fuentes-Martin 2010.16341 **Wilson** J. Aebischer et al. 1804.05033 **RGESolver** S. Di Noi, L. Silvestrini 2210.06838
  @1-loop in general EFT J. Aebischer et al. 2502.14030 M. Misiak, I. Nałęcz 2501.17134
  @2-loops in SMEFT (partial results) C. Duhr et al. 2503.01954
  S. Di Noi, R. Groeber 2507.10295 S. Di Noi et al. 2408.03252 U. Haisch 2503.06249 L. Born et al. 2410.07320

SMEFT & higher orders in the EFT expansion

Lagrangian

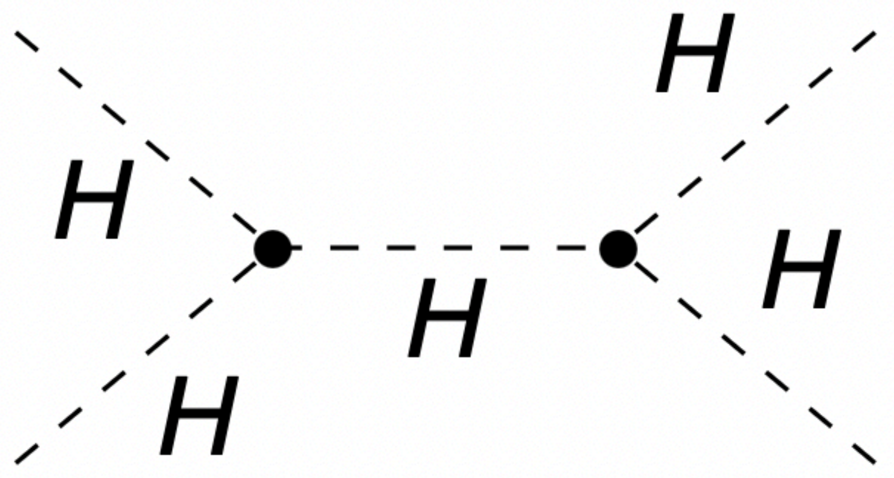
$$\mathscr{L}_{\text{SMEFT}} \supset (D_\mu\varphi)^\dagger(D^\mu\varphi) + V_{SM}(\varphi) + \underbrace{\frac{1}{\Lambda^2}C_\varphi\left(\varphi^\dagger\varphi\right)^3}_{\text{LO}} + \underbrace{\frac{1}{\Lambda^4}C_{\varphi^8}\left(\varphi^\dagger\varphi\right)^4}_{\text{NLO}} \qquad \varphi = \begin{pmatrix} \Phi^+ \\ \frac{1}{\sqrt{2}}\left(v + H + i\Phi^0\right) \end{pmatrix}$$

Vertex



$$-3i\lambda v + \underbrace{\frac{1}{\Lambda^2}15iv^3C_\varphi}_{\text{LO}} + \underbrace{\frac{1}{\Lambda^4}21iv^5C_{\varphi^8}}_{\text{NLO}}$$

Amplitude



$$-\frac{1}{s-M_H^2}\Bigg[9\lambda^2v^2 \underbrace{-\frac{1}{\Lambda^2}90\lambda v^4C_\varphi}_{\text{LO}} + \underbrace{\frac{1}{\Lambda^4}\left(225\lambda^4v^6(C_\varphi)^2 - 126\lambda v^6C_{\varphi^8}\right)}_{\text{NLO}}\Bigg]$$

SMEFT & higher orders in the EFT expansion

- So far most analyses and tools focused on dimension-6 SMEFT, with exceptions A. Dedes et al. 2011.07367 A. Capatti et al. 2205.15959 A. Dedes et al. 2506.12917

- Dimension-6^2 & dimensions-8 terms are not necessarily negligible

- SmeftFR v3 - tool designed for such calculations
  - Includes all dimension-6 SMEFT operators in the Warsaw basis B. Grządkowski et al. 1008.4884
  - All bosons dimension-8 SMEFT operators in the basis of C. Murphy 2005.00059

SmeftFR v3

`SmeftFR` v3 – Feynman rules generator for the Standard Model Effective Field Theory

A. Dedes[a], J. Rosiek[b,*], M. Ryczkowski[b], K. Suxho[a], L. Trifyllis[a]

[a]*Department of Physics, University of Ioannina, GR 45110, Ioannina, Greece*
[b]*Faculty of Physics, University of Warsaw, Pasteura 5, 02-093 Warsaw, Poland*

2302.01353, Comput.Phys.Commun. 294 (2024) 108943

Available at https://www.fuw.edu.pl/smeft/

SmeftFR v3 in a nutshell

1. Mathematica package based on FeynRules A. Alloul et al. 1310.1921
2. Allows consistent calculations of SMEFT vertices including LO $(1/\Lambda^2)$ and NLO $(1/\Lambda^4)$ terms in the EFT expansion
3. Includes predefined input schemes for the EW sector and CKM matrix
4. Outputs to LaTeX, FeynArts T. Hahn 0012260, UFO C. Degrande et al. 1108.2040
5. User can use subset of WCs relevant for a given analysis

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SmeftFR v3 and phenomenology
Double Higgs Production via Vector Boson Fusion in SMEFT

A. Dedes, J. Rosiek, MR 2506.12917

- **Double Higgs production leaves plenty space for BSM physics**

$$\sigma(pp \to hh) < 2.4(3.4) \times \sigma^{SM}(pp \to hh)$$ ATLAS 2211.01216 (CMS 2207.00043)

- **VBF-HH is suppressed in the SM…**

$$\sigma_{SM}^{ggF}(pp \to hh) > 10 \times \sigma_{SM}^{VBF}(pp \to hh)$$ B. Di Micco et al. 1910.00012

- **…but can be very sensitive to BSM physics**

- **Studied in many earlier works, including EFTs**
  F. Bishara et al.1611.03860 W. Kilian et al. 1808.05534 D. Domenech et al. 2208.05452

- **We studied NLO SMEFT effects (dimension-6^2 and dimension-8) using SmeftFR v3:**
  1. **Identified relevant WCs & estimated their numerical values**
  2. **Computed *WW>HH* & *ZZ>HH* helicity amplitudes**
  3. **Performed broader numerical analysis for HL-LHC**

SmeftFR v3 and phenomenology
Double Higgs Production via Vector Boson Fusion in SMEFT

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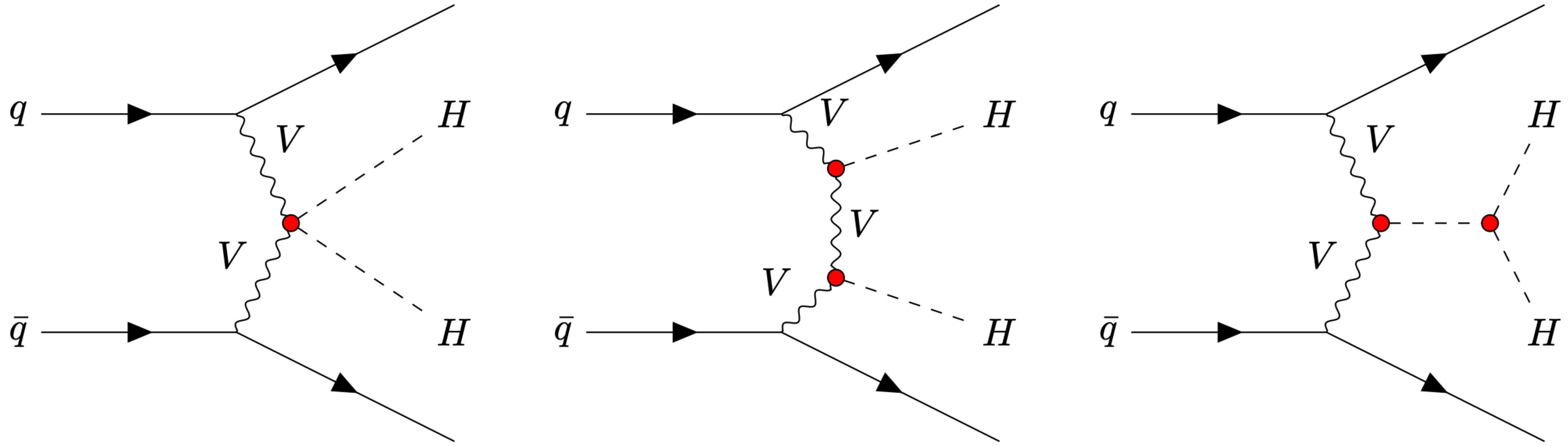

- **Process analysed**
  `p p > h h j j` **HL-LHC with** $\sqrt{s} = 14$ **TeV and** $\mathscr{L} = 3000$ **fb**$^{-1}$

- **Our analysis suggests rather small VBF-HH signal enhancement in most cases, below HL-LHC sensitivity** ATL-PHYS-PUB-2025-006

$$\mu_{VBF-HH} \equiv \Delta\sigma_{D6,8} \approx 10$$

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SmeftFR v3 and phenomenology
Double Higgs Production via Vector Boson Fusion in SMEFT

A. Dedes, J. Rosiek, MR 2506.12917

With some promising exceptions!

HL-LHC					
WC	$\frac{C}{1\ \mathrm{TeV}^{2,4}}$	$\Delta\sigma_{D6}$	ΔN_{D6}	$\Delta\sigma_{D6^2+D8}$	ΔN_{D6^2+D8}
$C_{\varphi\Box}$	2	2.62	332	4.96	810
$C_{\varphi W}$	1	6.35	1095	11.12	2070
$C_{\varphi^6\Box}$	-4	-	-	1.43	88
$C^{(1)}_{W^2\varphi^4}$	-4	-	-	3.80	573
BP3 scenario A		7.92	1415	23.09	4517
BP4 scenario A		7.92	1415	41.86	8357

BP3			
WC		$C_{\varphi\Box}$	$C_{\varphi W}$
$\frac{C}{1\ \mathrm{TeV}^{(2)}}$	A	2	1
	B	2	-1
	C	-2	1
	D	-2	-1

BP4					
WC		$C_{\varphi\Box}$	$C_{\varphi^6\Box}$	$C_{\varphi W}$	$C^{(1)}_{W^2\varphi^4}$
$\frac{C}{1\ \mathrm{TeV}^{(2,4)}}$	A	2	4	1	4
	B	2	4	-1	-4
	C	-2	-4	1	4
	D	-2	-4	-1	-4

$$\Delta\sigma_{D6,8} = (\sigma^{SMEFT}_{D6,8} - \sigma^{SM})/\sigma^{SM}, \quad \Delta N_{D6,8} = N^{SMEFT}_{D6,8} - N^{SM}$$

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SMEFT & global fits

Experimental results

Theory predictions (SM+SMEFT)

SMEFiT

v3 E. Celada et al. 2404.12809

Statistical methods

Posterior on WCs

$p(C_i)$

Other tools:
- **HEPfit** J. de Blas et al. 1910.14012
- **Fitmaker** J. Ellis et al. 2012.02779
- **smelli** J. Aebischer et al. 1810.07698

SMEFT & global fits

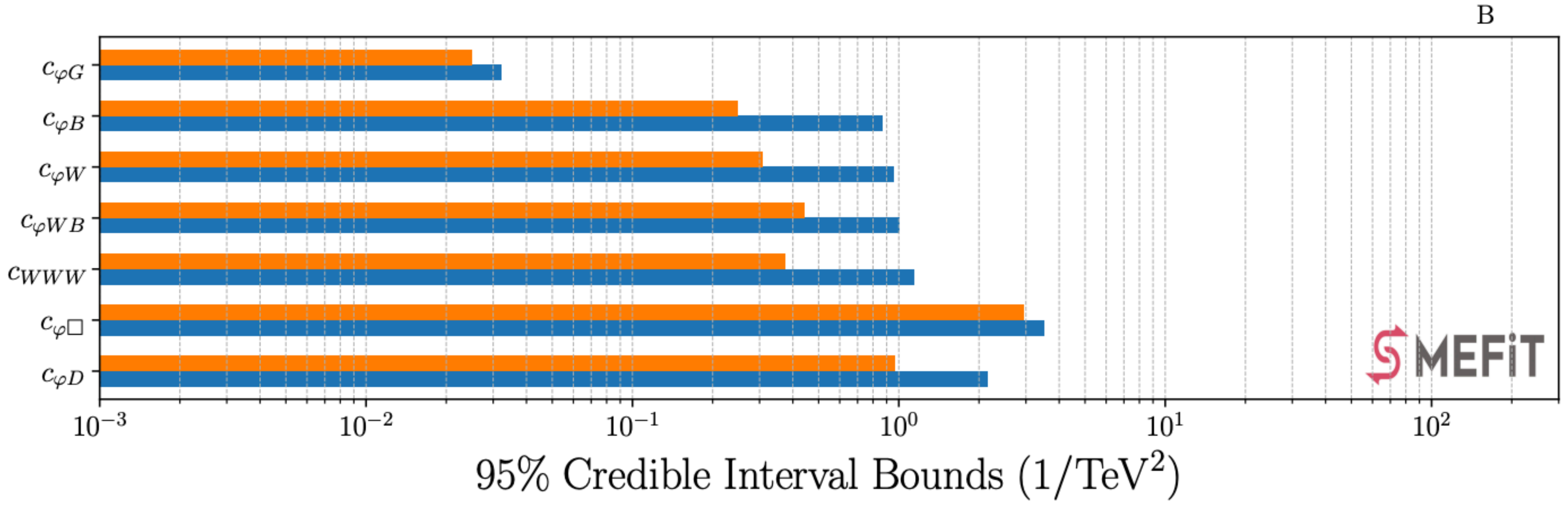
Experimental results

Theory predictions (SM+SMEFT)

These constraints can be taken as priors for further analyses

And combined with matching to get insights into underlying UV model

Statistical methods



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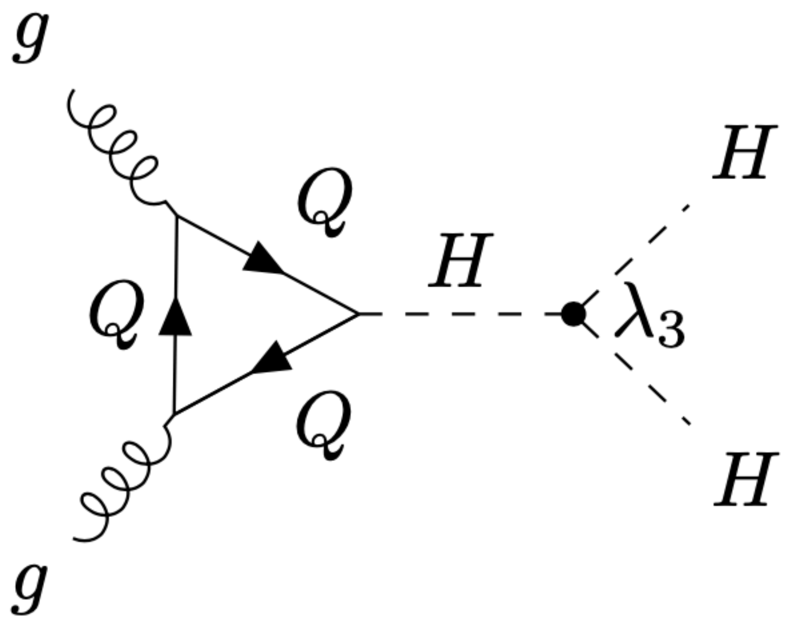
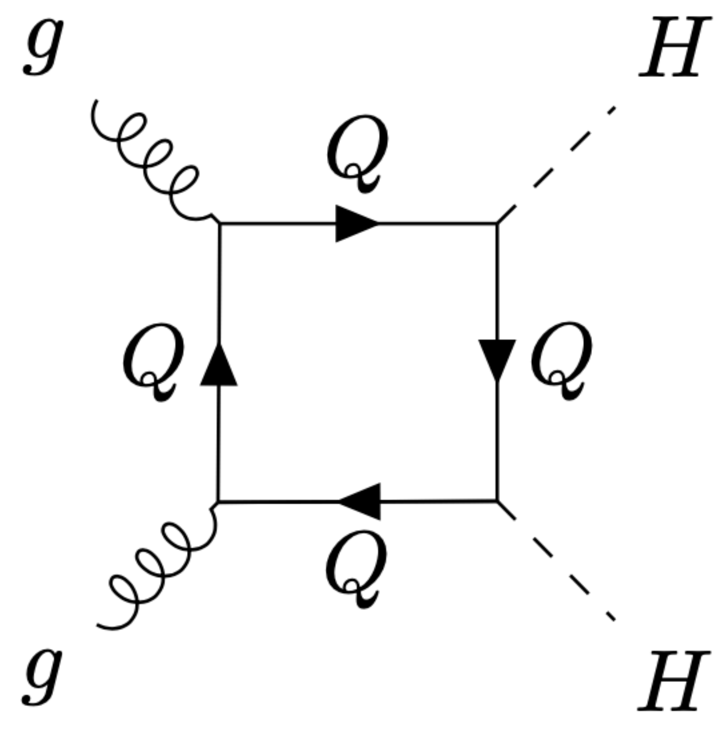
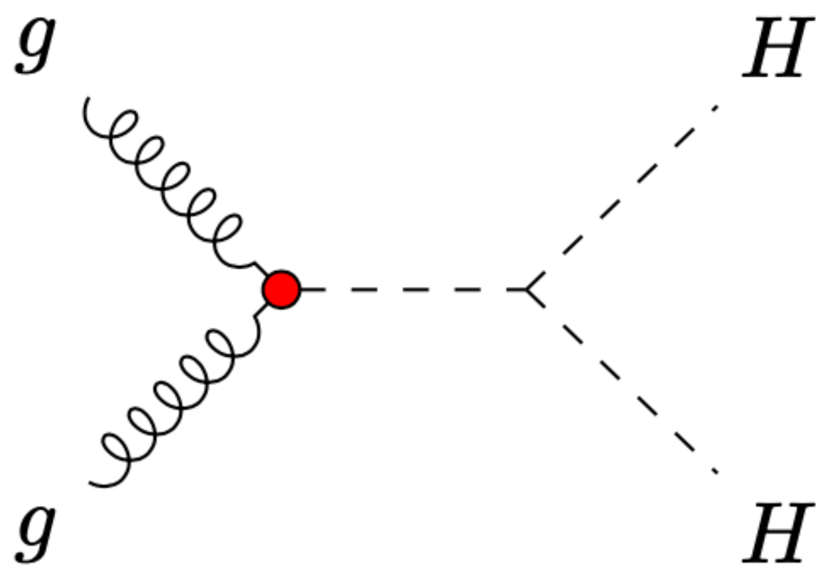
Matching: SMEFT and UV models

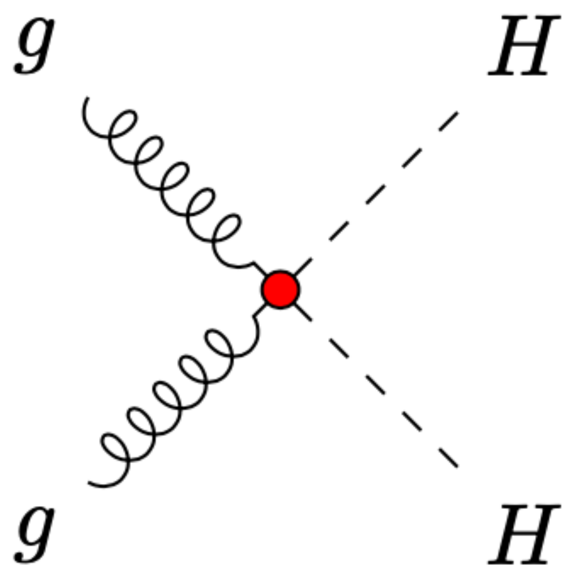
Heavy physics at low energies translates to non-zero WCs





$M_Q \gg E$





$$C^{\varphi G} = -\left(n_U \frac{Y_U^2}{M_U^2} + n_D \frac{Y_D^2}{M_D^2}\right) \frac{g_s^2}{48\pi^2}$$

Different UV models generate different patterns of WCs

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Matching: SMEFT and UV models

- Methods
  - Functional methods B. Henning et al. 1412.1837
  - Diagrammatic methods

  J. de Blas et al. 1711.10391 S. De Angelis, G. Durieux 2308.00035 M. Chala et al. 2411.12798

- Tools
  - CoDEx S. Das Bakshi et al. 1808.04403
  - Matchete J. Fuentes-Martin et al. 2212.04510
  - MarchMakerEFT A. Carmona et al. 2112.10787
  - mosca J. L. Miras, F. Vilches 2505.21353

- Dictionaries
  - Tree-level J. de Blas et al. 1711.10391
  - One-loop G. Guedes, P. Olgoso 2412.14253

(Some) key aspects of SMEFT and EFTs

- Operator bases & higher dimensions
- Phenomenology
  - Precision #1 - loops & RG evolution
  - Precision #2 - higher orders in the EFT expansion
  - Fits & matching to UV completions
- On-shell methods

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On-shell scattering amplitudes bootstrap approach

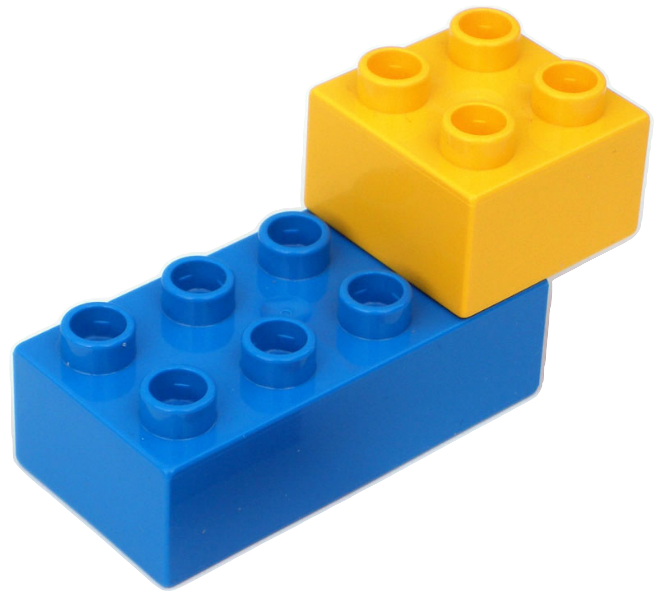
- Lorentz invariance
- Global symmetries
- Locality
- Unitarity & factorisation
- Helicity states & little group
- Physical DoF

- Simple scattering amplitudes
- Computational efficiency
- Emergence of gauge symmetry
- Bottom-up EFT without field redefinition ambiguity

On-shell amplitudes building blocks

- **Momenta**

$$p_{a\dot{b}} = -|p]_a \langle p|_{\dot{b}}, \qquad p^{\dot{a}b} = -|p\rangle^{\dot{a}} [p|^b .$$



- **Spin 1/2 external polarisations**

$$u_+(p) = |p], \quad u_-(p) = |p\rangle,$$
$$\bar{u}_+(p) = [p|, \quad \bar{u}_-(p) = \langle p|,$$

- **Spin 1 massless external polarisations**

$$\epsilon_-^\mu(p;q) = -\frac{\langle p|\gamma^\mu|q]}{\sqrt{2}\,[q\,p]}, \qquad \epsilon_+^\mu(p;q) = -\frac{\langle q|\gamma^\mu|p]}{\sqrt{2}\,\langle q\,p\rangle},$$

Amplitudes written in terms of 2-component Weyl spinors (bra/kets), momenta and s invariants

$$s_{ij} = (p_i + p_j)^2, \quad s_{ijk} = (p_i + p_j + p_k)^2$$

For review see e.g. H. Elvang, Y. Huang 1308.1697

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Some applications of on-shell methods

- **Widely used in the context of massless QCD from the 90s** M. Peskin 1101.2414
- **From 2017 on applications to**
  - Massive states N. Arkani-Hamed et al. 1709.04891
  - EFTs

  Building bases
  Y. Shadmi, Y. Weiss 1809.09644 G. Durieux et al. 1909.10551 M. A. Huber, S. De Angelis 2108.03669

  RGE running
  P. Baratella et al. 2005.07129 L. Bresciani et al. 2412.04160 J. Aebischer et al. 2502.14030

  Matching to UV models
  S. De Angelis, G. Durieux 2308.00035 M. Chala et al. 2411.12798

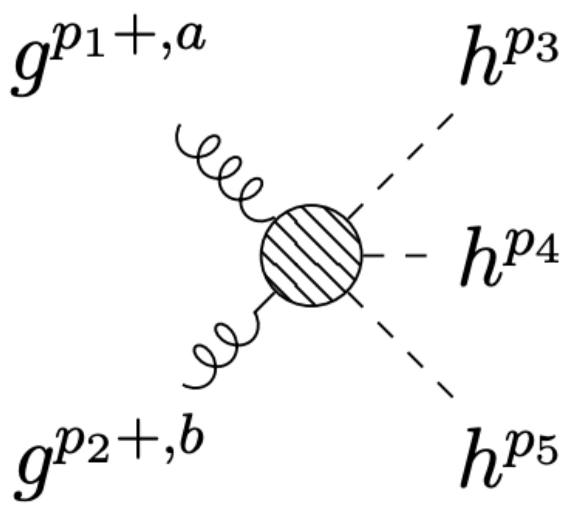
- **Application of the on-shell EFT to study SMEFT vs HEFT**
  R. Groeber, A. Rossia, MR 2509.02680

gg>hhh from on-shell EFT
SMEFT vs HEFT

Idea - extend existing gg>h and gg>hh results to gg>hhh, perform systematic matching to SMEFT and HEFT, identify their differences

R. Groeber, A. Rossia, MR 2509.02680

Amplitude



$$\mathcal{M}\left(g_1^{a,+}; g_2^{b,+}; h_3; h_4; h_5\right)_{\rm NF} = i\,\delta^{ab}\, c^{++,(1)}_{gghhh}[1|2]^2 + i\,\delta^{ab}\, c^{++,(2)}_{gghhh}\left([1|\mathbf{34}|2][1|\mathbf{43}|2] + [1|\mathbf{35}|2][1|\mathbf{53}|2] + [1|\mathbf{45}|2][1|\mathbf{54}|2]\right)$$

Matching

$$c^{++,(1)}_{gghhh} = \frac{1}{\Lambda^3}\sum_{i,j,k,l,m=0}\frac{c^{++,(1)(ijklm)}_{gghhh}}{\Lambda^{2(i+j+k+l+m)}} s_{12}^i\, s_{13}^j\, s_{14}^k\, s_{23}^l\, s_{24}^m\,,$$

$$c^{++,(2)}_{gghhh} = \frac{1}{\Lambda^7}\sum_{i,j,k,l,m=0}\frac{c^{++,(2)(ijklm)}_{gghhh}}{\Lambda^{2(i+j+k+l+m)}} s_{12}^i\, s_{13}^j\, s_{14}^k\, s_{23}^l\, s_{24}^m\,.$$

Dim-12

$$-i\,c^{++,(2)(00000)}_{gghhh} = \begin{cases} -\dfrac{1}{\Lambda}\dfrac{1}{2^{9/4}\sqrt{G_F}}\,C^{(1)}_{G^2\varphi^4D^4}, & \text{SMEFT}\,, \\[2mm] \dfrac{}{\Lambda}\dfrac{g_s^2\sqrt{G_F}}{2^{9/4}}\,C^{(1)}_{GHD^4(1)}, & \text{HEFT}\,. \end{cases}$$

NNNLO

gg>hhh from on-shell EFT
SMEFT vs HEFT

Amplitude	Helicity	Spinor structure	Coeff.	Dimension	Minimal order	
					SMEFT	HEFT
Three-point						
$gg \to h$	$++$	$[1\|2]^2$	c_{ggh}	$-1\,(1/\bar{\Lambda})$	$6\,(v/\Lambda^2)$	NLO*
$hh \to h$	-	-	c_{hhh}	$1\,(\bar{\Lambda})$	4	LO
Four-point						
$hh \to hh$	-	-	c_{4h}	0	4	LO
$gg \to hh$	$++$	$[1\|2]^2$	c^{++}_{gghh}	$-2\,(1/\bar{\Lambda}^2)$	$6\,(1/\Lambda^2)$	NLO*
	$+-$	$[1\|\mathbf{3}-\mathbf{4}\|2\rangle^2$	c^{+-}_{gghh}	$-4\,(1/\bar{\Lambda}^4)$	$8\,(1/\Lambda^4)$	NNLO*
Five-point						
$hh \to hhh$	-	-	c_{5h}	0	$6\,(v/\Lambda^2)$	LO
$gg \to hhh$	$++$	$[1\|2]^2$	$c^{++,(1)}_{gghhh}$	$-3\,(1/\bar{\Lambda}^3)$	$8\,(v/\Lambda^4)$	NLO*
	$++$	$[1\|\mathbf{34}\|2]^2$	$c^{++,(2)}_{gghhh}$	$-7\,(1/\bar{\Lambda}^7)$	$12\,(v/\Lambda^8)$	N^{3}LO*
	$+-$	$[1\|\mathbf{3}\|2\rangle^2$	c^{+-}_{gghhh}	$-5\,(1/\bar{\Lambda}^5)$	$10\,(v/\Lambda^6)$	NNLO*

Observable differences in power counting between SMEFT and HEFT

5P amplitude generate structure not present at 3P and 4P level and breaks naive SMEFT-HEFT correspondence

SMEFT and HEFT are not fundamentally different distinction lies in their convergence pattern

Extensions - heavy vector bosons, more Higgses, ...

Summing up

- **EFTs (and SMEFT in particular) are powerful but very complex tools in the BSM physics searches**

- **Recent advances cover:**
  - Construction of SMEFT operator bases (up to dim-12)
  - Higher precision calculations (loops & EFT expansion)
  - Fits & matching between SMEFT and UV models
  - Development of advanced tools streamlining calculations
  - Applications of on-shell methods
  - Other topics…

Thank you!