Dim-8 operators in double Higgs production

Vector Boson Fusion

Michał Ryczkowski

in collaboration with:
A. Dedes, J. Rosiek

based on project in progress

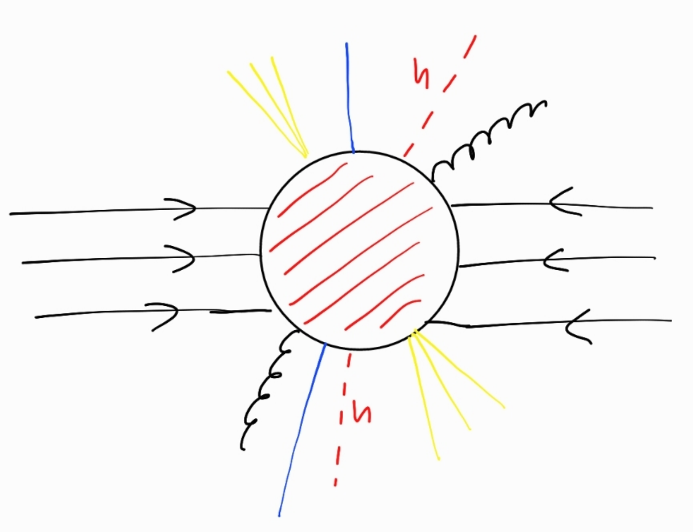
Effective Field Theory in Multiboson Production
Padova 11.06.2024

FACULTY OF PHYSICS
UNIVERSITY OF WARSAW

Outline

1. Double Higgs production - introduction
2. Di-Higgs production via ggF and VBF
3. Dim-6 and dim-8 bosonic SMEFT operators relevant for VBF di-Higgs
4. Assumptions & constraints
5. Helicity amplitudes & cross sections
6. Numerical simulations
7. Summary and next steps

Double Higgs production



Double Higgs production #1

- Understanding Higgs sector and mechanism of EWSB
- Probing Higgs self-coupling λ

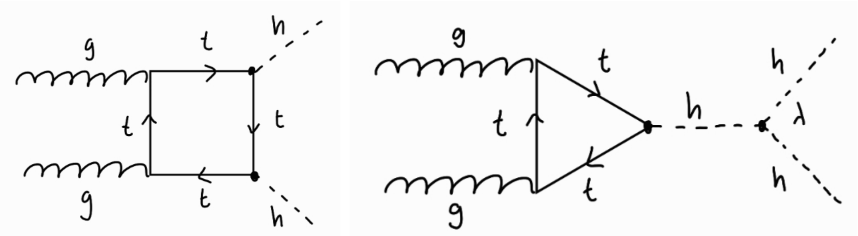
$$V(\phi) = -m^2\phi^\dagger\phi + \lambda\left(\phi^\dagger\phi\right)^2$$

- Potential sensitivity to BSM physics, with current constraints (LHC $\sqrt{s} = 13$ TeV):

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

Double Higgs production via gluon fusion (ggF)

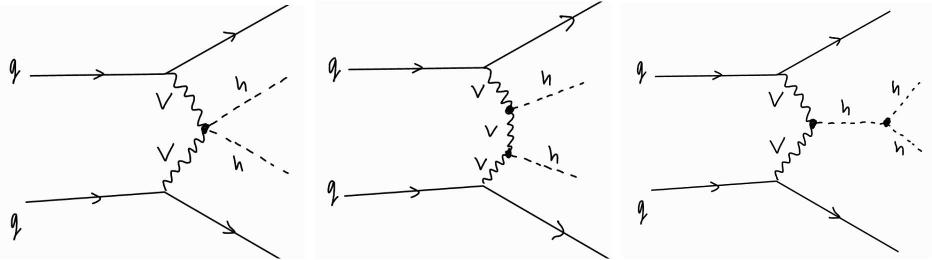
Main di-Higgs production channel:



SM & LHC with $\sqrt{s} = 14$ TeV at NNLO [2008.11626]:

$$\sigma_{SM}^{ggF}(pp \to hh) = 36.69^{+6\%}_{-23\%} \text{ fb}$$

Double Higgs production via Vector Boson Fusion (VBF)



SM & LHC with $\sqrt{s} = 14$ TeV at N^{3}LO [1811.07906]:

$$\sigma_{SM}^{VBF}(pp \to hhjj) = 2.055^{+0.001}_{-0.001} \text{ fb}$$

Double Higgs production via VBF

$$\sigma_{SM}^{VBF}(pp \to hhjj) < 10\% \times \sigma_{SM}^{ggF}(pp \to hh)$$

Di-Higgs production via VBF (see e.g. [1611.03860]):

- Very sensitive to BSM physics,
  small changes of the SM couplings can lead to striking increase in σ
- Can give us further insight into the EW sector and mechanism of EWSB
  e.g. by constraining $hhVV$ couplings

What is the maximal enhancement of VBF di-Higgs production in SMEFT at $\mathcal{O}\left(\frac{1}{\Lambda^4}\right)$ order of the EFT expansion?

Double Higgs production via VBF in SMEFT
Strategy of analysis

1. Identify & classify relevant dim-6 $\mathcal{O}\left(\frac{1}{\Lambda^2}\right)$ and dim-8 $\mathcal{O}\left(\frac{1}{\Lambda^4}\right)$ operators
2. Formulate analysis assumptions, take into account existing constraints on WCs
3. Calculate helicity amplitudes & cross sections
4. Identify leading behaviour and main SMEFT contributions
5. Run numerical MC simulations to formulate more precise predictions

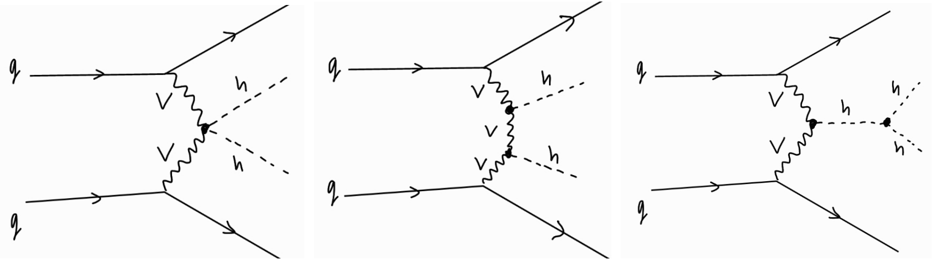
Introducing: SMEFT

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

- Q_i - higher dimensional gauge invariant operators in terms of SM fields
- C_i - Wilson coefficients
- Λ - new physics scale

Model independent way of studying BSM phenomena!

Double Higgs production via VBF in SMEFT #1



We're looking at hVV, $hhVV$ and hhh interactions!

Double Higgs production via VBF in SMEFT #2
Dim-6 operators

$X^2\varphi^2$		φ^6 and $\varphi^4 D^2$	
$Q_{\varphi W}$	$\varphi^\dagger\varphi\, W^I_{\mu\nu} W^{I\mu\nu}$	Q_φ	$(\varphi^\dagger\varphi)^3$
$Q_{\varphi\widetilde{W}}$	$\varphi^\dagger\varphi\, \widetilde{W}^I_{\mu\nu} W^{I\mu\nu}$	$Q_{\varphi\Box}$	$(\varphi^\dagger\varphi)\Box(\varphi^\dagger\varphi)$
$Q_{\varphi B}$	$\varphi^\dagger\varphi\, B_{\mu\nu} B^{\mu\nu}$	$Q_{\varphi D}$	$\left(\varphi^\dagger D^\mu\varphi\right)^* \left(\varphi^\dagger D_\mu\varphi\right)$
$Q_{\varphi\widetilde{B}}$	$\varphi^\dagger\varphi\, \widetilde{B}_{\mu\nu} B^{\mu\nu}$		
$Q_{\varphi WB}$	$\varphi^\dagger\tau^I\varphi\, W^I_{\mu\nu} B^{\mu\nu}$		
$Q_{\varphi\widetilde{W}B}$	$\varphi^\dagger\tau^I\varphi\, \widetilde{W}^I_{\mu\nu} B^{\mu\nu}$		

Table: Dimension-6 operators affecting $VV \to hh$ process (notation of 1704.03888)

$$\varphi = \begin{pmatrix} \Phi^+ \\ \frac{1}{\sqrt{2}}\left(v + h + i\Phi^0\right) \end{pmatrix}, \quad D_\mu = \partial_\mu + i\bar{g} B_\mu Y + i\bar{g} W^I_\mu T^I$$

$$W^I_{\mu\nu} = \partial_\mu W^I_\nu - \partial_\nu W^I_\mu - g\epsilon^{IJK} W^J_\mu W^K_\nu, \quad B_{\mu\nu} = \partial_\mu B_\nu - \partial_\nu B_\mu$$

Double Higgs production via VBF in SMEFT #3
Dim-8 operators

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

$X^3\varphi^2$		$X^2\varphi^4$	
$Q^{(1)}_{W^3\varphi^2}$ $Q^{(1)}_{W^2B\varphi^2}$	$\epsilon^{IJK}(\varphi^\dagger\varphi)W^{I\nu}_\mu W^{J\rho}_\nu W^{K\mu}_\rho$ $\epsilon^{IJK}(\varphi^\dagger\tau^I\varphi)B^{\ \nu}_\mu W^{J\rho}_\nu W^{K\mu}_\rho$ $\ldots$	$Q^{(1)}_{W^2\varphi^4}$ $Q^{(1)}_{WB\varphi^4}$ $Q^{(1)}_{B^2\varphi^4}$	$(\varphi^\dagger\varphi)^2 W^I_{\mu\nu}W^{I\mu\nu}$ $(\varphi^\dagger\varphi)(\varphi^\dagger\tau^I\varphi)W^I_{\mu\nu}B^{\mu\nu}$ $(\varphi^\dagger\varphi)^2 B_{\mu\nu}B^{\mu\nu}$

$X^2\varphi^2 D^2$		$X\varphi^4 D^2$	
$Q^{(1)}_{B^2\varphi^2D^2}$ $Q^{(1)}_{W^2\varphi^2D^2}$ $Q^{(1)}_{WB\varphi^2D^2}$	$(D^\mu\varphi^\dagger D^\nu\varphi)B_{\mu\rho}B_\nu^{\ \rho}$ $(D^\mu\varphi^\dagger D^\nu\varphi)W^I_{\mu\rho}W^{I\rho}_\nu$ $(D^\mu\varphi^\dagger\tau^I D_\mu\varphi)B_{\nu\rho}W^{I\nu\rho}$	$Q^{(1)}_{W\varphi^4D^2}$ $Q^{(1)}_{B\varphi^4D^2}$	$(\varphi^\dagger\varphi)(D^\mu\varphi^\dagger\tau^I D^\nu\varphi)W^I_{\mu\nu}$ $(\varphi^\dagger\varphi)(D^\mu\varphi^\dagger D^\nu\varphi)B_{\mu\nu}$ $\ldots$

Table: Classes of dimension-8 operators affecting $VV \to hh$ process (from [2005.00059])

Naive Dimensional Analysis (NDA)

Naive Dimensional Analysis (NDA) for WCs (followig 1604.06444):

$$\frac{C_i}{\Lambda^{D-4}} = \frac{g_*^{n_i-2}}{\Lambda^{D-4}}$$

- D - dimension of SMEFT operator
- n_i - number of fields involved
- $g_* \leq 4\pi$ - UV coupling to the SM

$$\text{e.g.}\ \ C_\varphi = g_*^4 c_\varphi, \quad C_{\varphi\Box} = g_*^2 c_{\varphi\Box}, \quad C_{\varphi^8} = g_*^6\, c_{\varphi^8}\ , \quad C_{\varphi^6\Box} = g_*^4\, c_{\varphi^6\Box}$$

- $c_i \leq 1$ - numbers that can be further suppressed e.g. by symmetries

Values of WCs

- Dim-6 - constraints from fits, assuming $\Lambda = 1$ TeV and following [2105.00006]

$$|C_{\varphi\Box}| \lesssim \pi, \quad |C_{\varphi D}| \lesssim 1, \quad |C_{\varphi W}| \lesssim 0.5, \quad |C_{\varphi B}| \lesssim 0.5, \quad |C_{\varphi WB}| \lesssim 0.5$$

- C_φ from di-Higgs production data, [2304.01968]:

$$-\pi^2 \lesssim C_\varphi \lesssim 2\pi$$

- Dim-8 - NDA without additional assumptions or constraints, with $c_i = 1$

Let's produce helicity amplitudes using ...

SmeftFR v3 - [2302.01353]

Comput.Phys.Commun. 294 (2024) 108943

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*

SmeftFR available at:

www.fuw.edu.pl/smeft

SmeftFR v3 - relevant features

1. Mathematica package using FeynRules [1310.1921]
2. Consistent calculation of SMEFT vertices up to $\frac{1}{\Lambda^4}$:
   all dim-6 operators in the Warsaw basis [1008.4884]
   all bosonic dim-8 operators in the basis of [2005.00059]
3. Output to LaTeX, FeynArts, UFO, ...
4. Predefined input schemes for the EW sector and CKM matrix

Di-Higgs via VBF
Process and setup

$$W^+(p_1,\lambda_1) + W^-(p_2,\lambda_1) \to h(p_3) + h(p_4)$$

- Dim-6 operators with maximal allowed values:

$$Q_\varphi \propto \mathcal{O}\left(1\right), \quad Q_{\varphi D} \propto \mathcal{O}\left(s\right), \quad Q_{\varphi\Box} \propto \mathcal{O}\left(s\right), \quad Q_{\varphi W} \propto \mathcal{O}\left(s\right)$$

- Dim-8 operators:

$$Q_{\varphi^8} \propto \mathcal{O}\left(1\right), \quad Q^{(1)}_{\varphi^4 D^4} \propto \mathcal{O}\left(s^2\right), \quad Q^{(1)}_{W^2\varphi^4} \propto \mathcal{O}\left(s\right), \quad Q^{(1)}_{W^2\varphi^2 D^2} \propto \mathcal{O}\left(s^2\right)$$

with Λ to ensure validity of EFT:

$$|C| \times \frac{s}{\Lambda^2} \ll 1$$

- $\pm$ chosen to maximize enhancement

SM amplitudes

$$\mathcal{M}_{\lambda_1\lambda_2} \equiv \mathcal{M}^{WWHH}_{\lambda_1\lambda_2}(\theta, s, G_F, M_W, M_Z, M_H, C_i)$$

$$\mathcal{M}^{SM}_{00} = \sqrt{2} G_F M_H^2 \left[1 + 2\left(1 - \frac{4}{\sin^2\theta}\right)\frac{M_W^2}{M_H^2}\right]$$

$$\mathcal{M}^{SM}_{\pm\pm} = 2\sqrt{2} G_F M_W^2, \quad \mathcal{M}^{SM}_{\pm\mp} = 0, \quad \mathcal{M}^{SM}_{0\pm} = \mathcal{M}^{SM}_{\pm 0} = 0$$

At most constant contribution plus terms $\mathcal{O}(1/s)$

SMEFT dim-6 and dim-6^2 amplitudes

$$\mathcal{M}_{OO} = -3\sqrt{2}C_\varphi\left(\frac{1}{G_F\Lambda^2}\right) - 20C_{\varphi W}\left(\frac{M_W^2}{\Lambda^2}\right) + \frac{1}{2}(4C_{\varphi\Box} - C_{\varphi D})\left(\frac{s}{\Lambda^2}\right) \quad \textbf{LO EFT}$$

$$-28\sqrt{2}C_{\varphi W}^2\left(\frac{M_W^2}{\Lambda^2}\right)\left(\frac{1}{G_F\Lambda^2}\right) + \sqrt{2}(4C_{\varphi\Box}^2 + \frac{1}{4}C_{\varphi D}^2)\left(\frac{1}{G_F\Lambda^2}\right)\left(\frac{s}{\Lambda^2}\right) \quad \textbf{NLO EFT}$$

$$\mathcal{M}_{TT} = (4C_{\varphi\Box} - C_{\varphi D})\left(\frac{M_W^2}{\Lambda^2}\right)$$

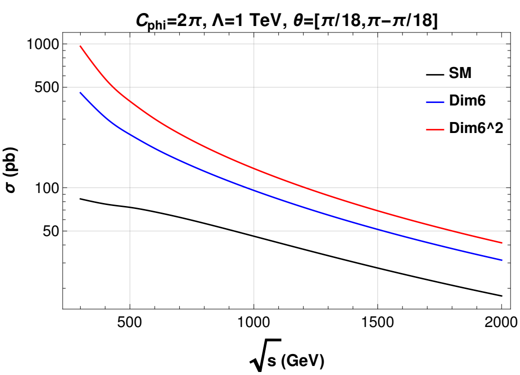
$$+\sqrt{2}(4C_{\varphi\Box}^2 + \frac{1}{4}C_{\varphi D}^2)\left(\frac{M_W^2}{\Lambda^2}\right)\left(\frac{1}{G_F\Lambda^2}\right) + 2\sqrt{2}C_{\varphi W}^2\left(\frac{1}{G_F\Lambda^2}\right)\left(\frac{s}{\Lambda^2}\right)$$

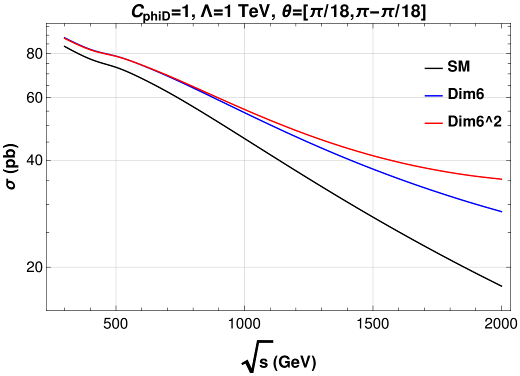
$$\mathcal{M}_{T_1T_2} = -(4C_{\varphi\Box} - C_{\varphi D})\left(\frac{M_W^2}{\Lambda^2}\right) + 2C_{\varphi W}\left(\frac{s}{\Lambda^2}\right)$$

$$-2\sqrt{2}(4C_{\varphi\Box}^2 + \frac{1}{4}C_{\varphi D}^2)\left(\frac{M_W^2}{\Lambda^2}\right)\left(\frac{1}{G_F\Lambda^2}\right) + 6\sqrt{2}C_{\varphi W}^2\left(\frac{1}{G_F\Lambda^2}\right)\left(\frac{s}{\Lambda^2}\right)$$

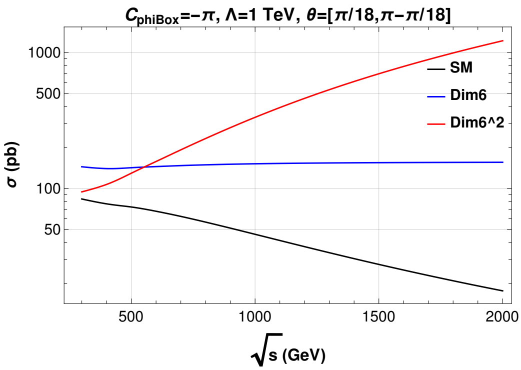
$$\mathcal{M}_{OT} = 16i\cot\theta\, C_{\varphi W}\left(\frac{\sqrt{s}M_W}{\Lambda^2}\right) + 16\sqrt{2}iC_{\varphi W}^2\cot\theta\left(\frac{1}{G_F\Lambda^2}\right)\left(\frac{\sqrt{s}M_W}{\Lambda^2}\right)$$

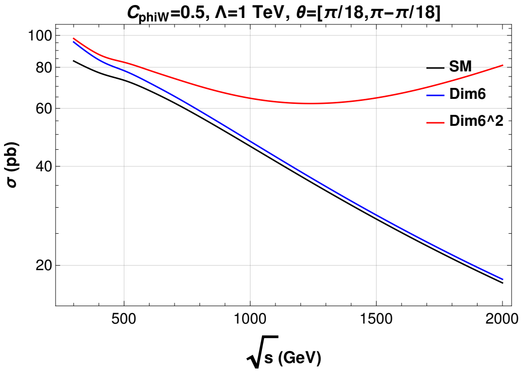
SMEFT dim-6 and dim-6^2 cross sections





SMEFT dim-6 and dim-6^2 cross sections





SMEFT dim-8 amplitudes

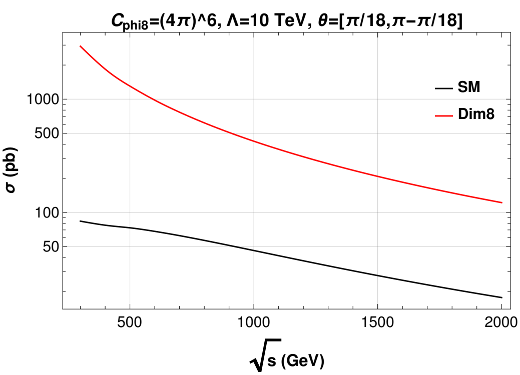
$$\mathcal{M}_{OO} = -6C_{\varphi^8}\left(\frac{1}{G_F^2\Lambda^4}\right) - \frac{1}{8}C^{(1)}_{\varphi^4 D^4}\left(\cos^2\theta + 1\right)\left(\frac{s^2}{\Lambda^4}\right)$$
$$-14\sqrt{2}C^{(1)}_{W^2\varphi^4}\left(\frac{M_W^2}{\Lambda^2}\right)\left(\frac{1}{G_F\Lambda^2}\right) + \frac{1}{2}C^{(1)}_{W^2\varphi^2 D^2}(\sin^2\theta + 1)\left(\frac{M_W^2}{\Lambda^2}\right)\left(\frac{s}{\Lambda^2}\right)$$

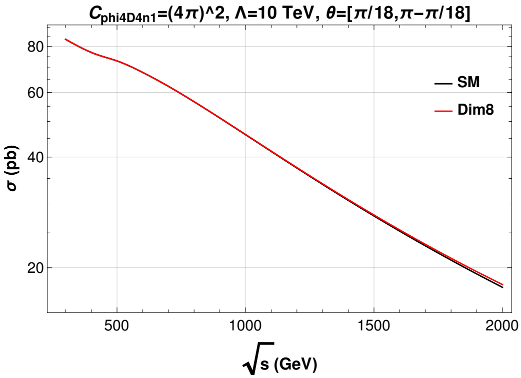
$$\mathcal{M}_{TT} = -\frac{1}{4}C^{(1)}_{\varphi^4 D^4}\sin^2\theta\left(\frac{M_W^2}{\Lambda^2}\right)\left(\frac{s}{\Lambda^2}\right) + \frac{1}{8}C^{(1)}_{W^2\varphi^2 D^2}\sin^2\theta\left(\frac{s^2}{\Lambda^4}\right)$$

$$\mathcal{M}_{T_1T_2} = -\frac{1}{4}C^{(1)}_{\varphi^4 D^4}\sin^2\theta\left(\frac{M_W^2}{\Lambda^2}\right)\left(\frac{s}{\Lambda^2}\right) + 3\sqrt{2}C^{(1)}_{W^2\varphi^4}\left(\frac{1}{G_F\Lambda^2}\right)\left(\frac{s}{\Lambda^2}\right) + \frac{1}{4}C^{(1)}_{W^2\varphi^2 D^2}\left(\frac{s^2}{\Lambda^4}\right)$$

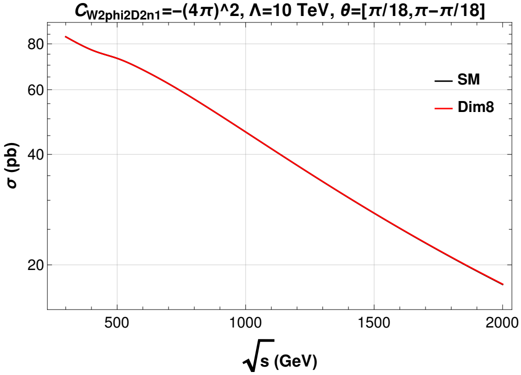
$$\mathcal{M}_{OT} = -\frac{i}{4}C^{(1)}_{\varphi^4 D^4}\sin 2\theta\left(\frac{s^{3/2}M_W}{\Lambda^4}\right) - 4C^{(1)}_{W^2\varphi^4}\cot\theta\left(\frac{s^{1/2}M_W}{\Lambda^2}\right)\left(\frac{1}{G_F\Lambda^2}\right) - \frac{i}{4}C^{(1)}_{W^2\varphi^2 D^2}\sin 2\theta\left(\frac{s^{3/2}M_W}{\Lambda^4}\right)$$

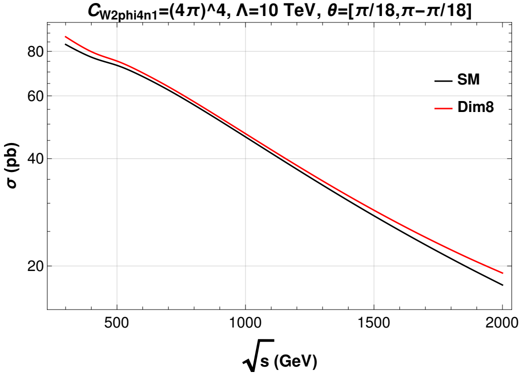
SMEFT dim-8 cross sections





SMEFT dim-8 cross sections





Initial conclusions

1. Potential strong enhancement at dim-6 and dim-6^2 - especially $C_{\varphi\Box}$
2. Importance of terms $\propto s$ for larger energies
3. Effects of dim-6^2 terms can be important
4. At dim-8 enhancement much more moderate
5. For dim-8 NDA more important than energy dependence

Let's see how it translates to MC simulations!
Work in progress...

Numerical analysis

```
p p > h h j j
```

1. `MG5` [1106.0522] with `UFO` models generated using `SmeftFR`
2. Only one non-zero C_i at time
3. Dim-6 - maximal WCs allowed by constraints from fits
4. Dim-8 - NDA
5. HL-LHC with $\sqrt{s} = 14$ TeV and $\mathcal{L} = 3000$ fb^{-1}
6. VBS cuts (following [1611.03860] and [1802.02366]:)

$$M_{jj} > 500 \text{ GeV}, \quad \Delta\eta_{jj} > 3, \quad M_{hh} > 400 \text{ GeV}, \ldots$$

Numerical analysis HL-LHC
dim-6 and dim-6^2

WC	Cross section (pb)	Events
SM	0.000198	594
C_φ	0.00618	1852
$C_\varphi + C_\varphi^2$	0.00618	1852
$C_{\varphi\Box}$	0.000469	1408
$C_{\varphi\Box} + C_{\varphi\Box}^2$	0.001291	3873
$C_{\varphi D}$	0.000203	609
$C_{\varphi D} + C_{\varphi D}^2$	0.000203	609
$C_{\varphi W}$	0.000241	724
$C_{\varphi W} + C_{\varphi W}^2$	0.000263	789

Table: `p p > h h j j` cross sections for HL-LHC with $\sqrt{s} = 14$ TeV and $\mathcal{L} = 3000$ fb^{-1}.

Numerical analysis
dim-8

$$\frac{C^{(1)}_{W^2\varphi^4}}{\Lambda^4} = \frac{(4\pi)^4}{\Lambda^4}, \qquad \frac{C^{(1)}_{W^2\varphi^2 D^2}}{\Lambda^4} = \frac{(4\pi)^2}{\Lambda^4}$$

	$\Lambda = 6$ TeV		$\Lambda = 10$ TeV	
WC	Cross section (pb)	No events	Cross section (pb)	No events
SM	0.000465	13	0.000465	13
$C^{(1)}_{W^2\varphi^2 D^2}$	0.000470	14	0.000466	13
$C^{(1)}_{W^2\varphi^4}$	0.01605	481	0.0006852	20

Table: `p p > h h j j` cross sections for LHC with $\sqrt{s} = 13$ TeV and $\mathcal{L} = 30$ fb^{-1}.

OLD RESULTS

Summary

1. Di-Higgs VBF production interesting and “promising” process
2. Large number of dim-6 and dim-8 bosonic SMEFT operators contributing
3. NDA as a source of estimation for dim-8 operators
4. $WW \to HH$ reveals potential enhancement from $\mathcal{O}(1)$, $\mathcal{O}(s)$ and $\mathcal{O}(s^2)$ terms
5. Initial MC results suggest potential impact of dim-6 and dim-6^2 and limited dim-8

Next steps & future directions?

1. Finish thorough `MG5` study including final states
2. More rigorous inclusion of constraints on dim-6 and dim-8 WCs
3. Inclusion of remaining classes of WCs and $ZZ \to HH$ process
4. Matching to particular UV models for more realistic picture
5. Effects of fermionic dim-8 operators?
6. ggF?

Thank you!