Double Higgs Production via Vector Boson Fusion in SMEFT

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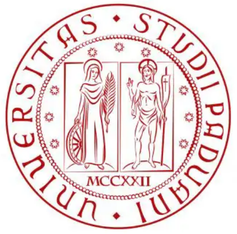
with A. Dedes and J. Rosiek

LHC EFT & Higgs WG Meetings 2025

CERN 03.12.2025



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Why study double Higgs production?

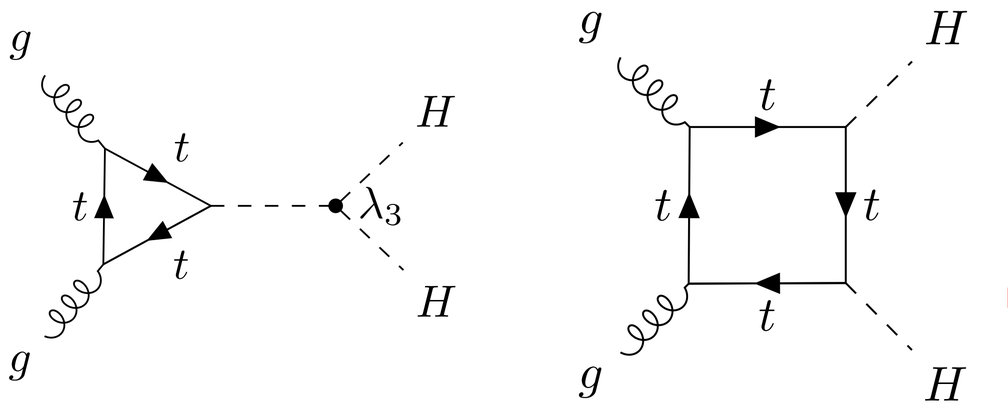
- **Probing trilinear Higgs self-coupling, the nature of Higgs potential and the stability of the electroweak vacuum**

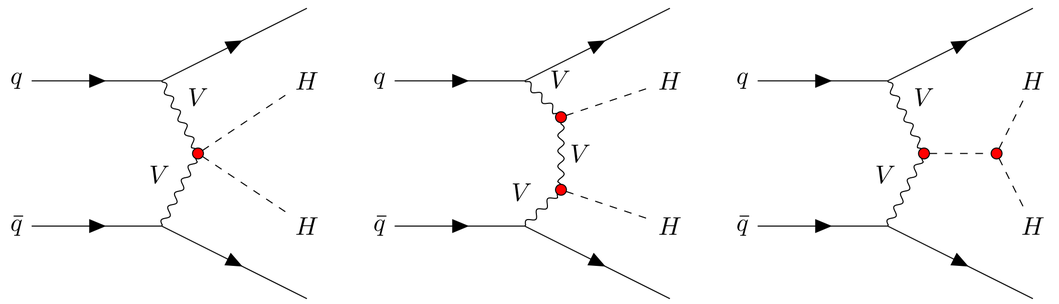
- **Plenty of space for the BSM physic**

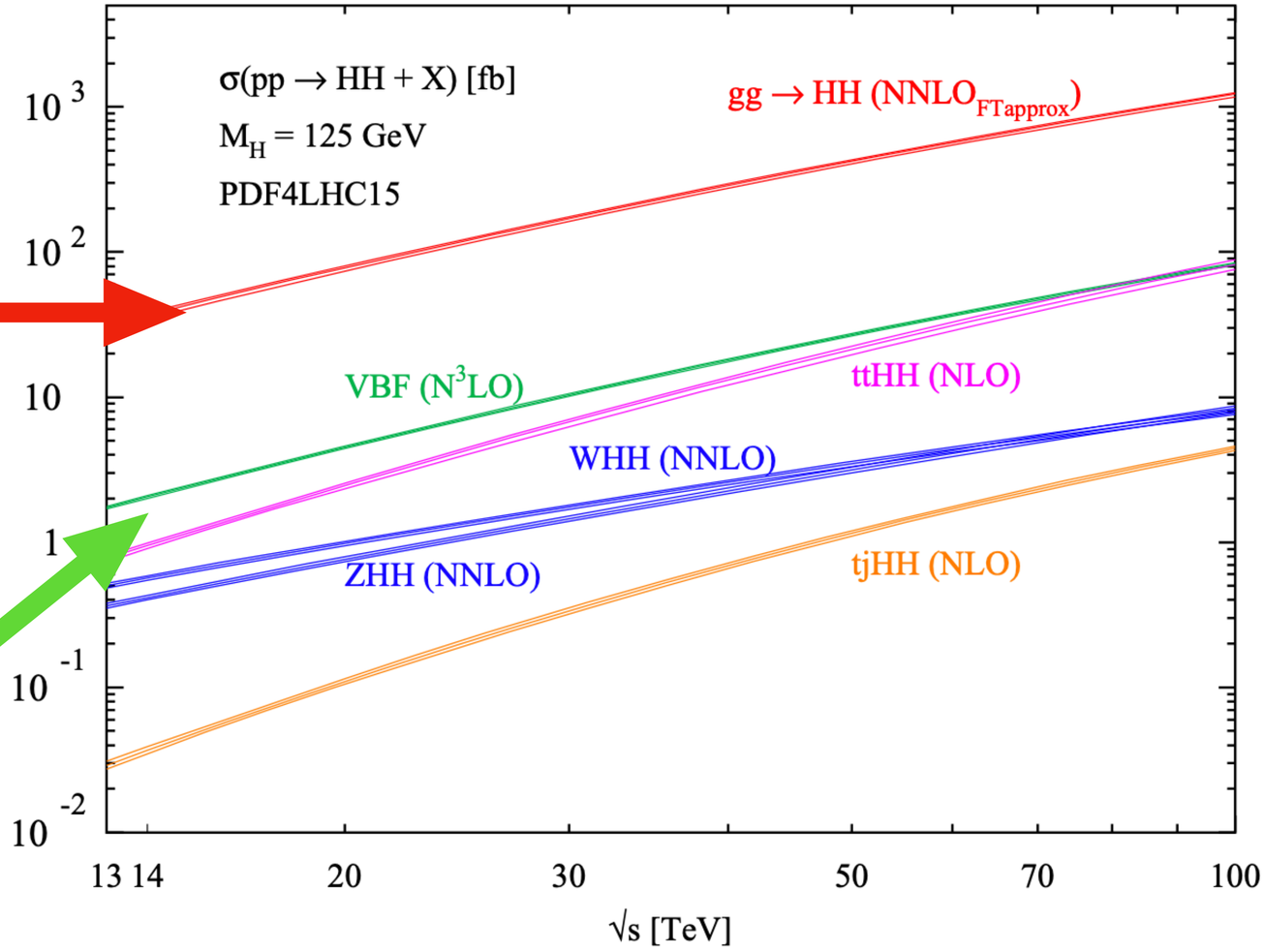
$$\sigma(pp \to hh) < 2.4 \times \sigma^{SM}(pp \to hh) \quad \text{ATLAS 2211.01216}$$

$$\sigma(pp \to hh) < 3.4 \times \sigma^{SM}(pp \to hh) \quad \text{CMS 2207.00043}$$

Double Higgs production channels

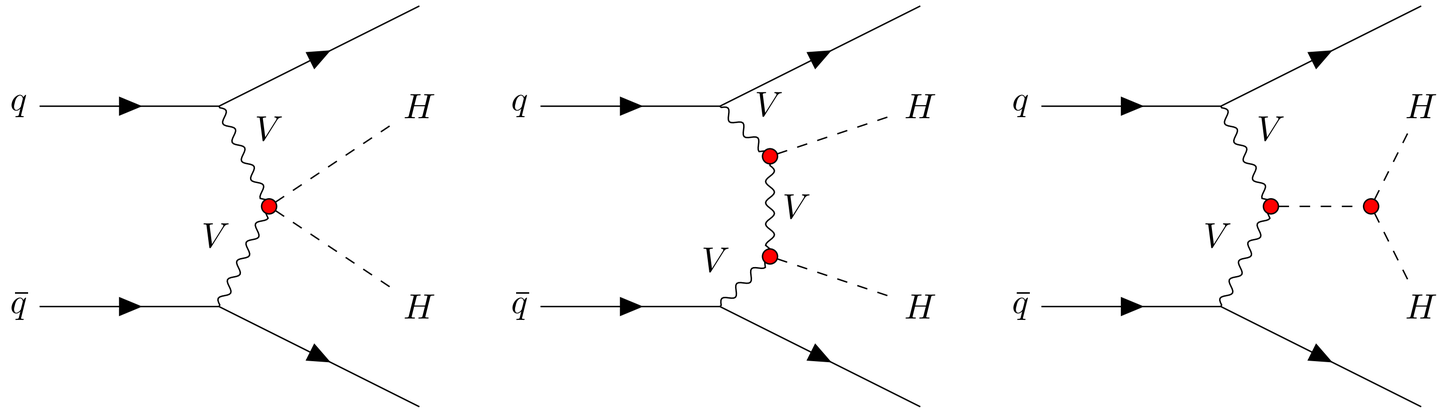






B. Di Micco et al. 1910.00012

VBF double Higgs production



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

BUT

- **Clean experimental signature with two forward jets with a large rapidity gap**
- **Potential significant enhancement due to the BSM physics**

Standard Model Effective Field Theory (SMEFT)

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

- **Model independent description of heavy & weakly coupled BSM physics**
- C_i **- dimensionless Wilson coefficients**
- Q_i **- higher dimensional effective operators of dimension** d_i
- Λ **- new physics scale - power counting**

Our approach to study VBF double Higgs production

- **VBF double Higgs 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, …

- **This work aims at studying NLO SMEFT (dim-6^2 and dim-8) effects**

- **Realistically estimate possible enhancement for HL-LHC**

SMEFT Wilson coefficients

- **Representative set of 20 non-CPV SMEFT WCs affecting $VV \to hh$ process**
- **6 dimension-6 operators in the Warsaw basis**
  B. Grzadkowski et al. 1008.4884
- **14 dimension-8 operators in the basis of**
  C. Murphy 2005.00059

Dimension-6		Dimension-8	
φ^6		φ^8	
Q_φ	$(\varphi^\dagger\varphi)^3$	Q_{φ^8}	$(\varphi^\dagger\varphi)^4$
$\varphi^4 D^2$		$\varphi^4 D^4$	
$Q_{\varphi\Box}$	$(\varphi^\dagger\varphi)\Box(\varphi^\dagger\varphi)$	$Q^{(1)}_{\varphi^4 D^4}$	$(D_\mu\varphi^\dagger D_\nu\varphi)(D^\nu\varphi^\dagger D^\mu\varphi)$
$Q_{\varphi D}$	$(\varphi^\dagger D^\mu\varphi)^*(\varphi^\dagger D_\mu\varphi)$	$Q^{(2)}_{\varphi^4 D^4}$	$(D_\mu\varphi^\dagger D_\nu\varphi)(D^\nu\varphi^\dagger D^\mu\varphi)$
		$Q^{(3)}_{\varphi^4 D^4}$	$(D_\mu\varphi^\dagger D^\mu\varphi)(D_\nu\varphi^\dagger D^\nu\varphi)$
		$\varphi^6 D^2$	
		$Q_{\varphi^6 D^2}$	$(\varphi^\dagger\varphi)(\varphi^\dagger D_\mu\varphi)^*(\varphi^\dagger D^\mu\varphi)$
		$Q_{\varphi^6\Box}$	$(\varphi^\dagger\varphi)^2\Box(\varphi^\dagger\varphi)$
$X^2\varphi^2$		$X^2\varphi^4$	
$Q_{\varphi W}$	$\varphi^\dagger\varphi\, W^I_{\mu\nu}W^{I\mu\nu}$	$Q^{(1)}_{W^2\varphi^4}$	$(\varphi^\dagger\varphi)^2 W^I_{\mu\nu}W^{I\mu\nu}$
$Q_{\varphi B}$	$\varphi^\dagger\varphi\, B_{\mu\nu}B^{\mu\nu}$	$Q^{(1)}_{B^2\varphi^4}$	$(\varphi^\dagger\varphi)^2 B_{\mu\nu}B^{\mu\nu}$
$Q_{\varphi WB}$	$\varphi^\dagger\tau^I\varphi\, W^I_{\mu\nu}B^{\mu\nu}$	$X^2\varphi^2 D^2$	
		$Q^{(1)}_{W^2\varphi^2 D^2}$	$(D^\mu\varphi^\dagger D^\nu\varphi)W^I_{\mu\rho}W^{I\rho}_\nu$
		$Q^{(2)}_{W^2\varphi^2 D^2}$	$(D^\mu\varphi^\dagger\tau^I D^\nu\varphi)W^I_{\mu\rho}W^\rho_\nu$
		$Q^{(1)}_{B^2\varphi^2 D^2}$	$(D^\mu\varphi^\dagger D^\nu\varphi)B_{\mu\rho}B^\rho_\nu$
		$Q^{(2)}_{B^2\varphi^2 D^2}$	$(D^\mu\varphi^\dagger D_\mu\varphi)B_{\nu\rho}B^{\nu\rho}$
		$X\varphi^4 D^2$	
		$Q^{(1)}_{W\varphi^4 D^2}$	$(\varphi^\dagger\varphi)(D^\mu\varphi^\dagger\tau^I D^\nu\varphi)W^I_{\mu\nu}$
		$Q^{(1)}_{B\varphi^4 D^2}$	$(\varphi^\dagger\varphi)(D^\mu\varphi^\dagger D^\nu\varphi)B_{\mu\nu}$

Dim-6 WCs

- C_φ **(and** C_{φ^8}**) from** κ_λ **constraints**

  L. Alasfar et al. 2304.01968, J. ter Hoeve et al. 2504.05974

$\kappa_{\lambda_3} \in [-1.2, 7.2]$ **ATLAS 2024**

$\kappa_{\lambda_3} \in [-1.2, 7.5]$ **CMS 2025**

$$-\frac{14}{\text{TeV}^2} \lesssim \frac{C_\varphi}{\Lambda^2} \lesssim \frac{5}{\text{TeV}^2}$$

Same κ_λ

$$-\frac{10}{\text{TeV}^2} \lesssim \frac{C_\varphi}{\Lambda^2} \lesssim \frac{4}{\text{TeV}^2}$$

$$-\frac{32}{\text{TeV}^4} \lesssim \frac{C_{\varphi^8}}{\Lambda^4} \lesssim \frac{7.5}{\text{TeV}^4}$$

- **All other dim-6 WCs from global fits, SMEFiT3.0**

  E. Celada et al. 2404.12809

$$\left|\frac{C_{\varphi\Box}}{\Lambda^2}\right| \lesssim \frac{2}{\text{TeV}^2}, \quad \left|\frac{C_{\varphi D}}{\Lambda^2}\right| \lesssim \frac{1.5}{\text{TeV}^2}, \quad \left|\frac{C_{\varphi W}}{\Lambda^2}\right| \lesssim \frac{1}{\text{TeV}^2}, \quad \left|\frac{C_{\varphi B}}{\Lambda^2}\right| \lesssim \frac{1}{\text{TeV}^2}, \quad \left|\frac{C_{\varphi WB}}{\Lambda^2}\right| \lesssim \frac{1}{\text{TeV}^2}$$

- **No corresponding results for dim-8 WCs, some attempts at setting constraints** A. Capatti et at. 2205.15959

Naive Dimensional Analysis

- **Following R. Contino et al. 1604.06444 we utilise power counting called Naive Dimensional Analysis (NDA)**

- **D - mass dimension, n_i - number of fields involved, g_* - NP coupling, Λ - NP scale, c_i - additional suppression factor**

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

$$C_{\varphi^8} = g_*^6\, c_{\varphi^8}\,, \quad C_{\varphi^6\Box} = g_*^4\, c_{\varphi^6\Box}\,, \quad C_{\varphi^6 D^2} = g_*^4\, c_{\varphi^6 D^2}\,, \quad C^{(i)}_{\varphi^4 D^4} = g_*^2\, c^{(i)}_{\varphi^4 D^4}$$

$$C^{(i)}_{V^2\varphi^4} = g_*^4\, c^{(1)}_{V^2\varphi^4}\,, \qquad C^{(i)}_{V^2\varphi^2 D^2} = g_*^2\, c^{(1)}_{V^2\varphi^2 D^2}\,, \qquad C^{(i)}_{V\varphi^4 D^2} = g_*^3\, c^{(1)}_{V\varphi^4 D^2}$$

Values of g_* and dim-8 WCs

- **We can use NDA to estimate values of dim-8 WCs**
- **Global fits (and κ_λ for C_φ and C_{φ^8}) to dim-6 WCs can provide estimate of g_***
- ***Optimistic* scenario - choose $C_{\varphi\Box}$ as the least constrained with $c_{\varphi\Box} = 1$, assume single g_***

$$\left|\frac{C_{\varphi\Box}}{\Lambda^2}\right| \lesssim \frac{2}{\text{TeV}^2} \qquad \& \qquad C_{\varphi\Box} = g_*^2$$

- **Also include theoretical considerations (loop expansion criterion, unitarity bounds, positivity bounds, …)**

$$g_* \leq min\left(\sqrt{2}\frac{\Lambda}{1\ \text{TeV}}, 4\pi\right)$$

Summing up our assumptions…

- C_φ, C_{φ^8} **from** κ_λ**, other dim-6 WCs from global fits**
- **Dim-8 WCs - NDA with single** g_* **coupling with value extracted from** $C_{\varphi\Box}$

$$\left|\frac{C_{\varphi\Box}}{\Lambda^2}\right| \lesssim \frac{2}{\text{TeV}^2} \quad \& \quad C_{\varphi\Box} = g_*^2\, c_{\varphi\Box} \quad \Rightarrow \quad g_* \leq min\left(\sqrt{2}\frac{\Lambda}{1\ \text{TeV}}, 4\pi\right)$$

- **EFT validity criterion**

$$\frac{s_{MAX}}{\Lambda^2} < 1$$

- ***Optimistic*** **scenario, but sufficient to estimate leading effects**
- **Truncation at the amplitude level**

The analysis

- **Study of the VBF double Higgs production for HL-LHC**
- **Comparison between LO (dim-6) and NLO (dim-6^2 and dim-8) effects**
- **Comparison between s dependent and independent contributions**
- **First study one non-zero WC at a time**
- **Then consider a more complicated pattern of WCs**

$WW \to HH$

Dim-6 amplitude

$$\mathscr{M}_{00}^{WW,D6} = -3\sqrt{2}C_{\varphi}\left(\frac{1}{G_F\Lambda^2}\right) - 20C_{\varphi W}\left(\frac{M_W^2}{\Lambda^2}\right) + \frac{1}{2}(4C_{\varphi\Box} - C_{\varphi D})\left(\frac{s}{\Lambda^2}\right) - 28\sqrt{2}C_{\varphi W}^2\left(\frac{M_W^2}{\Lambda^2}\right)\left(\frac{1}{G_F\Lambda^2}\right) + \sqrt{2}(4C_{\varphi\Box}^2 + \frac{1}{4}C_{\varphi D}^2)\left(\frac{1}{G_F\Lambda^2}\right)\left(\frac{s}{\Lambda^2}\right)$$

$$\mathscr{M}_{\pm\pm}^{WW,D6} = -(4C_{\varphi\Box} - C_{\varphi D})\left(\frac{M_W^2}{\Lambda^2}\right) + 2C_{\varphi W}\left(\frac{s}{\Lambda^2}\right) - 2\sqrt{2}(4C_{\varphi\Box}^2 + \frac{1}{4}C_{\varphi D}^2)\left(\frac{M_W^2}{\Lambda^2}\right)\left(\frac{1}{G_F\Lambda^2}\right) + 6\sqrt{2}C_{\varphi W}^2\left(\frac{1}{G_F\Lambda^2}\right)\left(\frac{s}{\Lambda^2}\right)$$

$$\mathscr{M}_{\pm\mp}^{WW,D6} = (4C_{\varphi\Box} - C_{\varphi D})\left(\frac{M_W^2}{\Lambda^2}\right) + \sqrt{2}(4C_{\varphi\Box}^2 + \frac{1}{4}C_{\varphi D}^2)\left(\frac{M_W^2}{\Lambda^2}\right)\left(\frac{1}{G_F\Lambda^2}\right) + 2\sqrt{2}C_{\varphi W}^2\left(\frac{1}{G_F\Lambda^2}\right)\left(\frac{s}{\Lambda^2}\right)$$

$$\mathscr{M}_{0\pm}^{WW,D6} = -4\sqrt{2}\cot\theta C_{\varphi W}\left(\frac{\sqrt{s}M_W}{\Lambda^2}\right) - 8C_{\varphi W}^2\cot\theta\left(\frac{1}{G_F\Lambda^2}\right)\left(\frac{\sqrt{s}M_W}{\Lambda^2}\right)$$

MC analysis setup #1

- **MG5 with UFO models generated with SmeftFR v3**
  A. Dedes, J. Rosiek, MR, K. Suxho, L. Trifyllis 2302.01353

- **VBF double Higgs production process**

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

MC analysis setup #2

- **We employ VBF cuts**
  J. Kalinowski et al. 1802.02366, A. Dedes et al. 2011.07367

$$M_{jj} \geq 700 \text{ GeV}, \quad \Delta\eta_{jj} \geq 5, \quad |\eta_j| \leq 4.5, \quad p_{Tj} \geq 25 \text{ GeV}, \quad M_{hh} \geq 400 \text{ GeV}$$

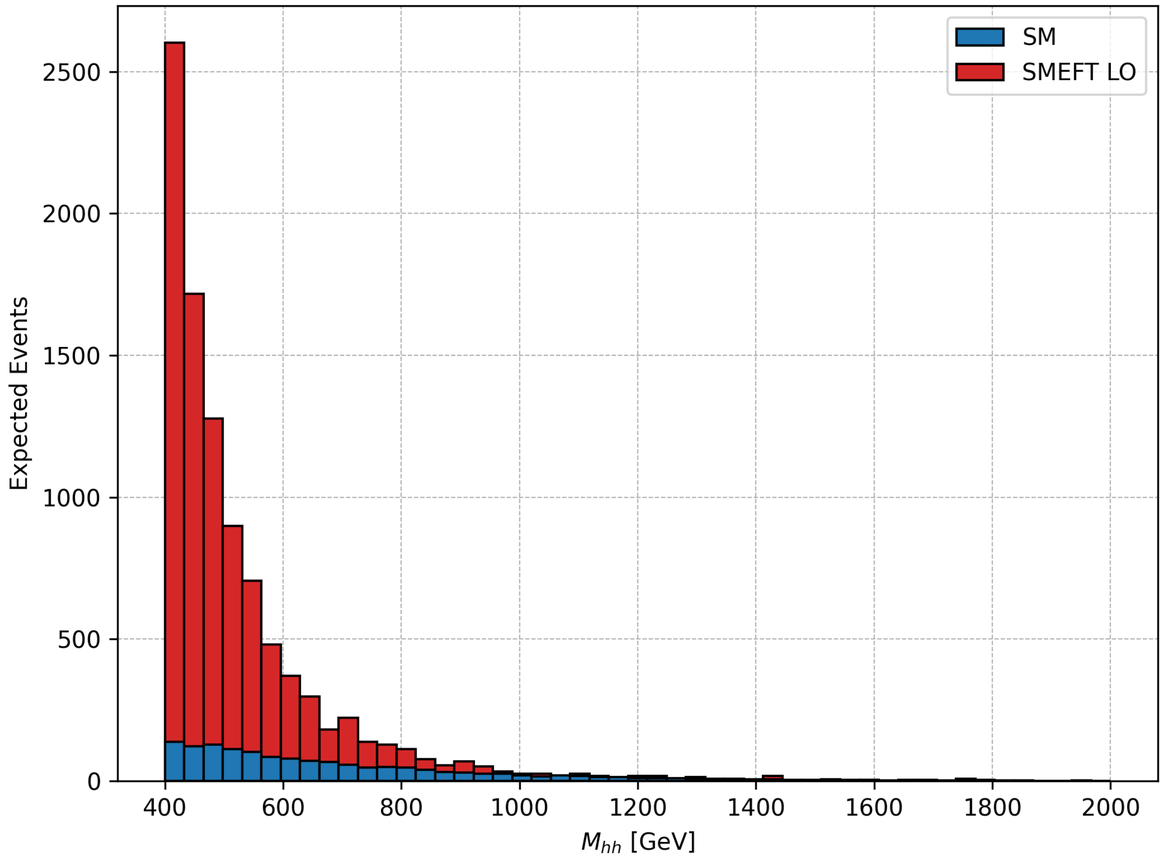
- **Study enhancement defined as**

$$\Delta\sigma_{D6,8} = \sigma_{D6,8}^{SMEFT}/\sigma^{SM}$$

- **Projected HL-LHC sensitivity** ATL-PHYS-PUB-2025-006

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

VBF double Higgs enhancement with κ_λ



$$\frac{C_\varphi}{\Lambda^2} = -\frac{13.8}{\text{TeV}^2}, \quad \sqrt{s}_{MAX} \approx 2\ \text{TeV}$$

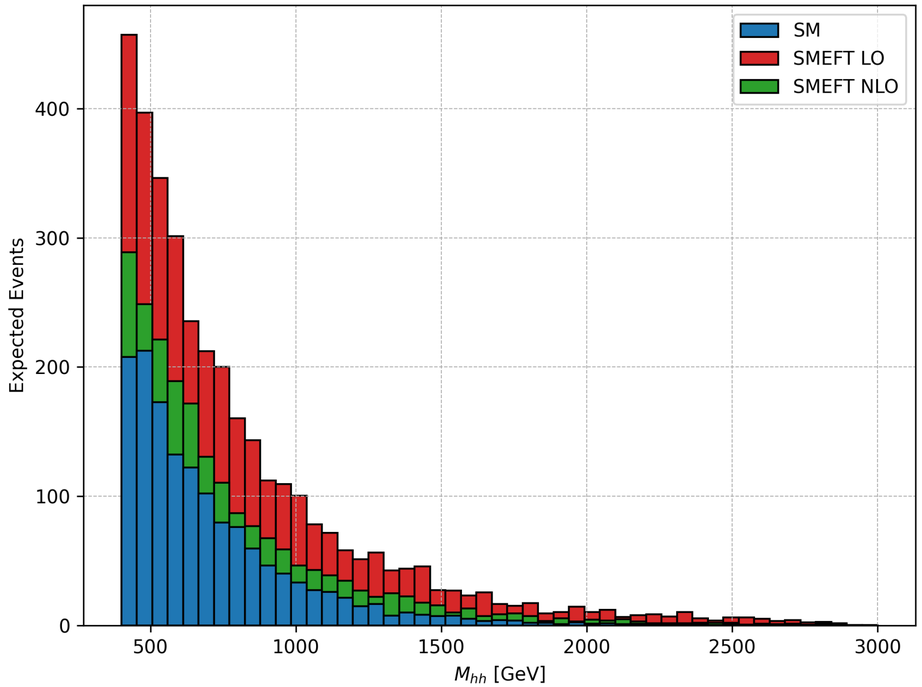
$$\frac{\sigma_{SMEFT}}{\sigma_{SM}} = 22$$

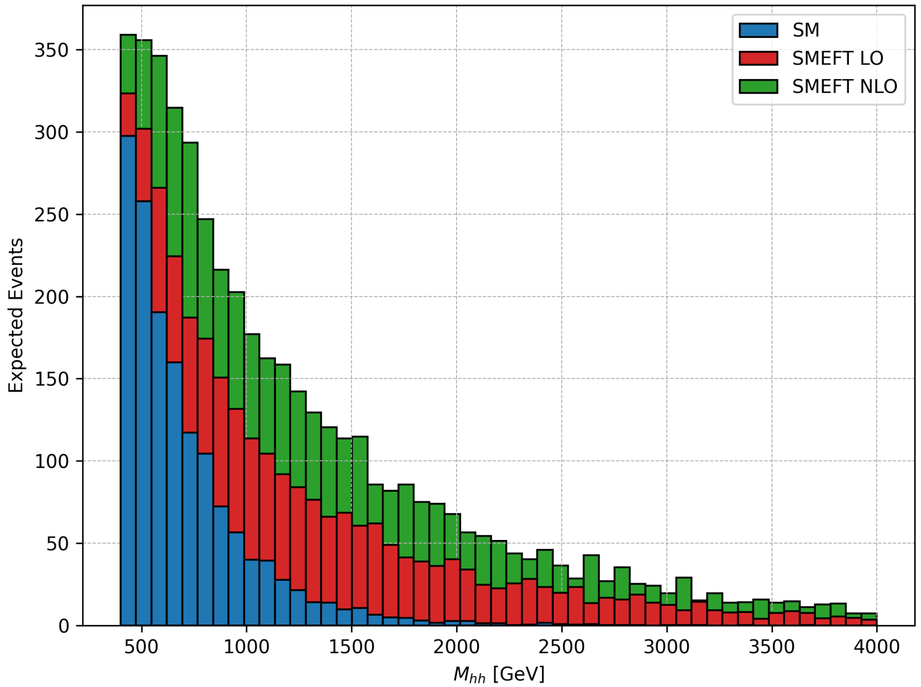
Strong enhancement but would also affect gluon-fusion channel!

VBF double Higgs enhancement with dim-6 WCs

$$\frac{C_{\varphi\Box}}{\Lambda^2} = -\frac{2}{\text{TeV}^2}, \quad \sqrt{s}_{MAX} \approx 3 \text{ TeV}$$

$$\frac{C_{\varphi W}}{\Lambda^2} = \frac{1}{\text{TeV}^2}, \quad \sqrt{s}_{MAX} \approx 4 \text{ TeV}$$





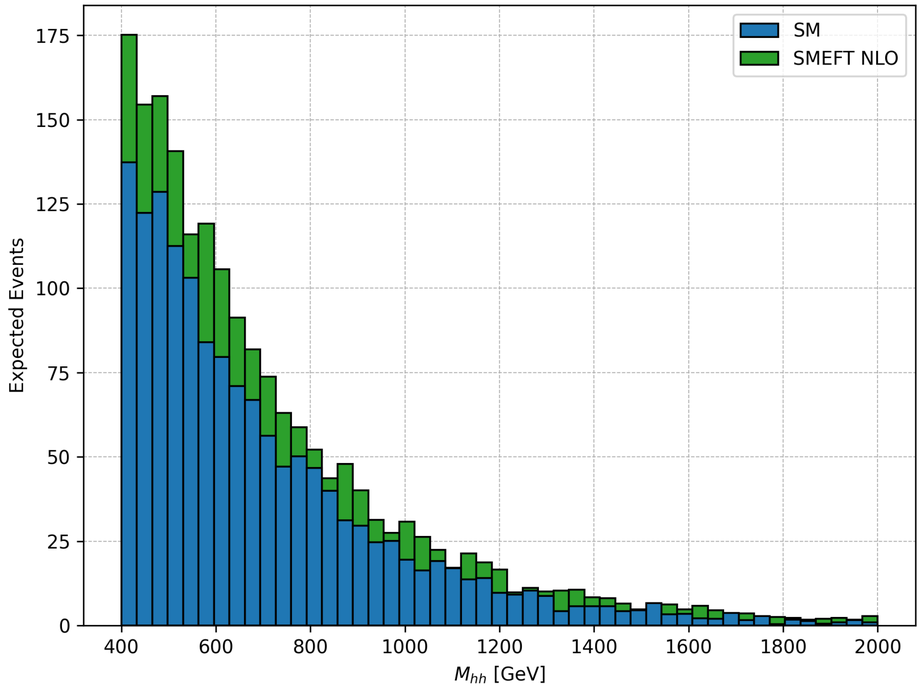
$$\frac{\sigma^{LO}_{SMEFT}}{\sigma_{SM}} = 2.42 \quad \frac{\sigma^{NLO}_{SMEFT}}{\sigma_{SM}} = 1.41$$

$$\frac{\sigma^{LO}_{SMEFT}}{\sigma_{SM}} = 1.85 \quad \frac{\sigma^{NLO}_{SMEFT}}{\sigma_{SM}} = 2.72$$

VBF double Higgs enhancement with dim-8 WCs #1

$$\frac{C_{\varphi^6\Box}}{\Lambda^4} = \frac{g_*^4}{\Lambda^4} = -\frac{4}{1\ \text{TeV}^4}$$

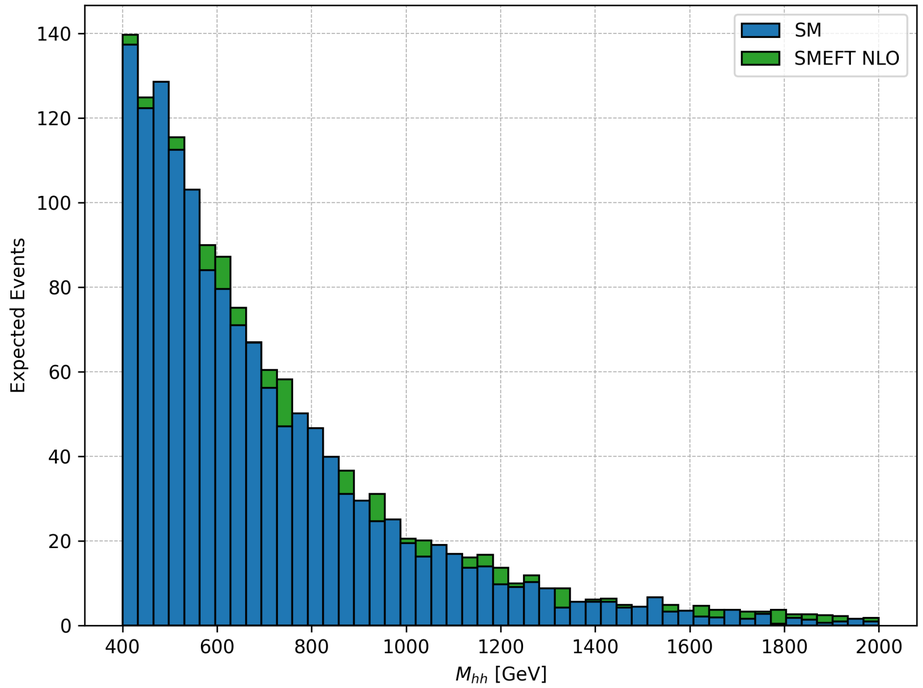
$$g_* = \sqrt{2}\frac{\Lambda}{1\ \text{TeV}}, \quad \sqrt{s}_{MAX} = \Lambda \approx 2\ \text{TeV}$$



$$\frac{\sigma_{SMEFT}^{NLO}}{\sigma_{SM}} = 1.30$$

$$\frac{C_{\varphi^4 D^4}^{(3)}}{\Lambda^4} = \frac{g_*^2}{\Lambda^4} = \frac{2}{1\ \text{TeV}^2}\frac{1}{\Lambda^2} = \frac{0.5}{1\ \text{TeV}^4}$$

$$g_* = \sqrt{2}\frac{\Lambda}{1\ \text{TeV}}, \quad \sqrt{s}_{MAX} = \Lambda \approx 2\ \text{TeV}$$

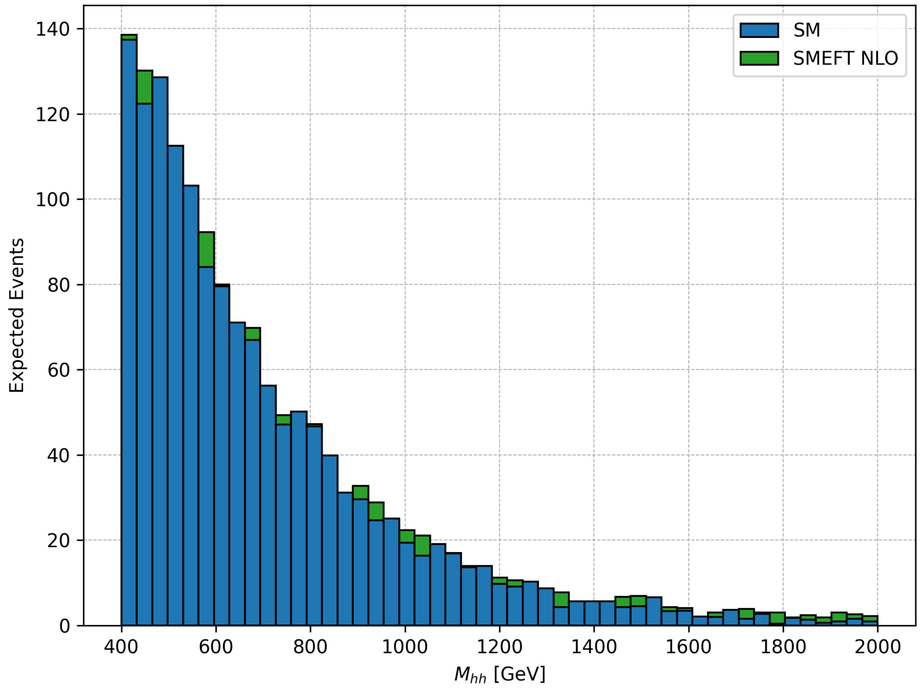


$$\frac{\sigma_{SMEFT}^{NLO}}{\sigma_{SM}} = 1.05$$

VBF double Higgs enhancement with dim-8 WCs #2

$$\frac{C^{(1)}_{W^2\varphi^2D^2}}{\Lambda^4} = \frac{g_*^2}{\Lambda^4} = \frac{2}{1\ \text{TeV}^2}\frac{1}{\Lambda^2} = \frac{0.5}{1\ \text{TeV}^4}$$

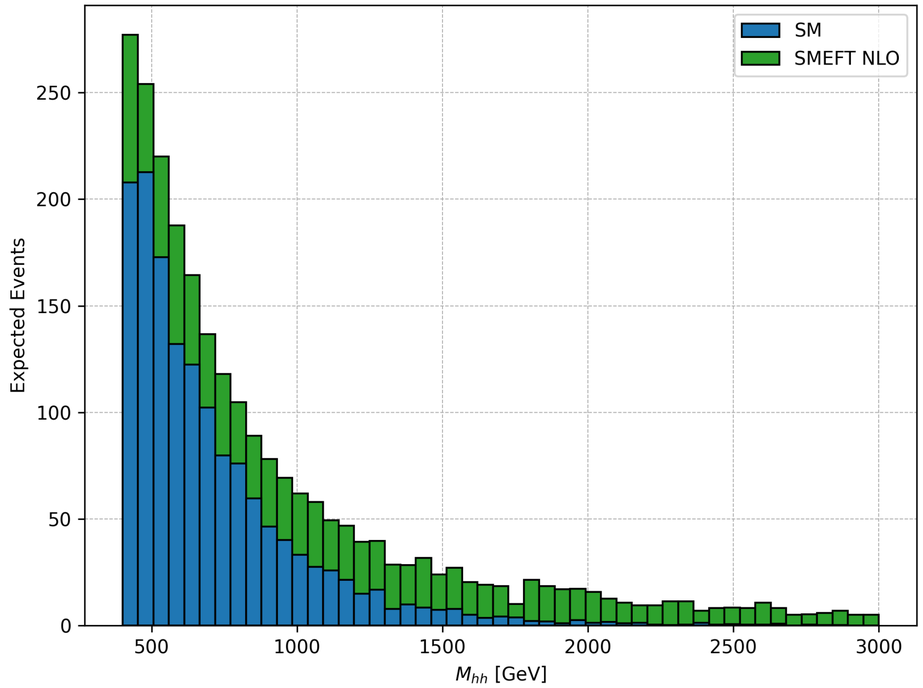
$$g_* = \sqrt{2}\frac{\Lambda}{1\ \text{TeV}}, \quad \sqrt{s}_{MAX} = \Lambda \approx 2\ \text{TeV}$$



$$\frac{\sigma^{NLO}_{SMEFT}}{\sigma_{SM}} = 1.11$$

$$\frac{C^{(1)}_{W^2\varphi^4}}{\Lambda^4} = \frac{g_*^4}{\Lambda^4} = \frac{4}{1\ \text{TeV}^4}$$

$$g_* = \sqrt{2}\frac{\Lambda}{1\ \text{TeV}}, \quad \sqrt{s}_{MAX} = \Lambda \approx 3\ \text{TeV}$$



$$\frac{\sigma^{NLO}_{SMEFT}}{\sigma_{SM}} = 1.43$$

Several non-zero WCs at a time

- **UV completions generate more than one non-zero WCs**
- **Interference between WCs may be source of strong enhancement**
- **BP1 and BP2 follow from the scalar singlet model**
- **BP3 and BP4 illustrate enhancement with $\kappa_\lambda = 1$**

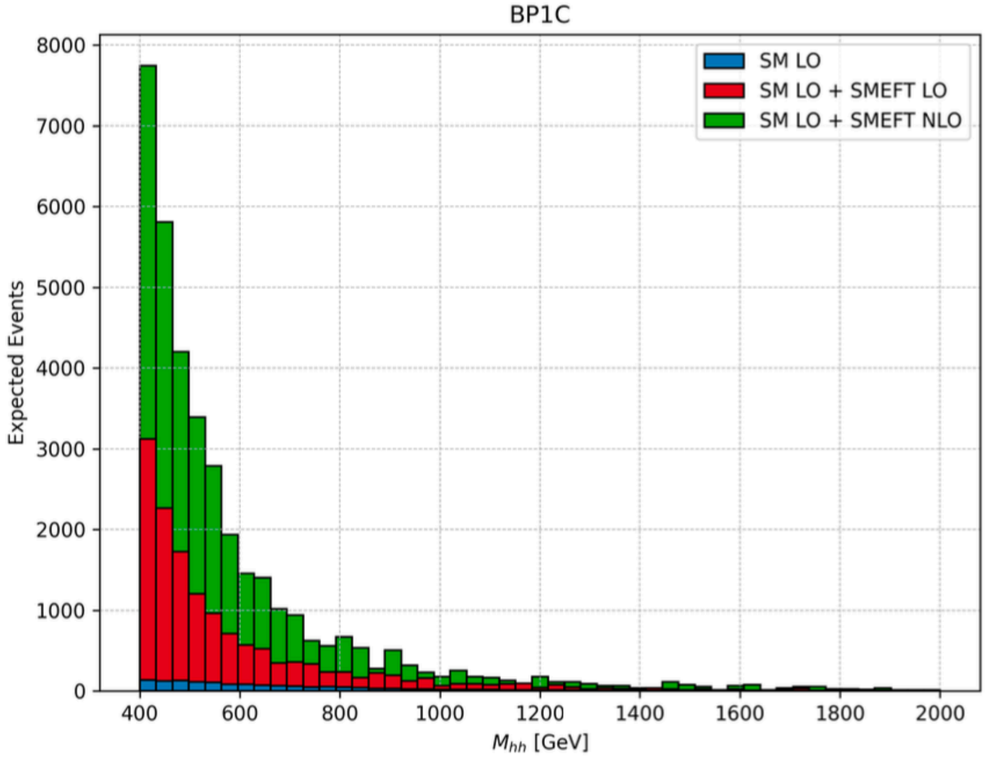
BP1			
WC		C_φ	$C_{\varphi\Box}$
$\frac{C}{1\ \mathrm{TeV}^2}$	A	4.7	2
	B	4.7	-2
	C	-13.8	2
	D	-13.8	-2

BP2					
WC		C_φ	C_{φ^8}	$C_{\varphi\Box}$	$C_{\varphi^6\Box}$
$\frac{C}{1\ \mathrm{TeV}^{(2,4)}}$	A	3.8	7.4	2	4
	B	3.8	7.4	-2	-4
	C	-10	-13.6	2	4
	D	-10	-13.6	-2	-4

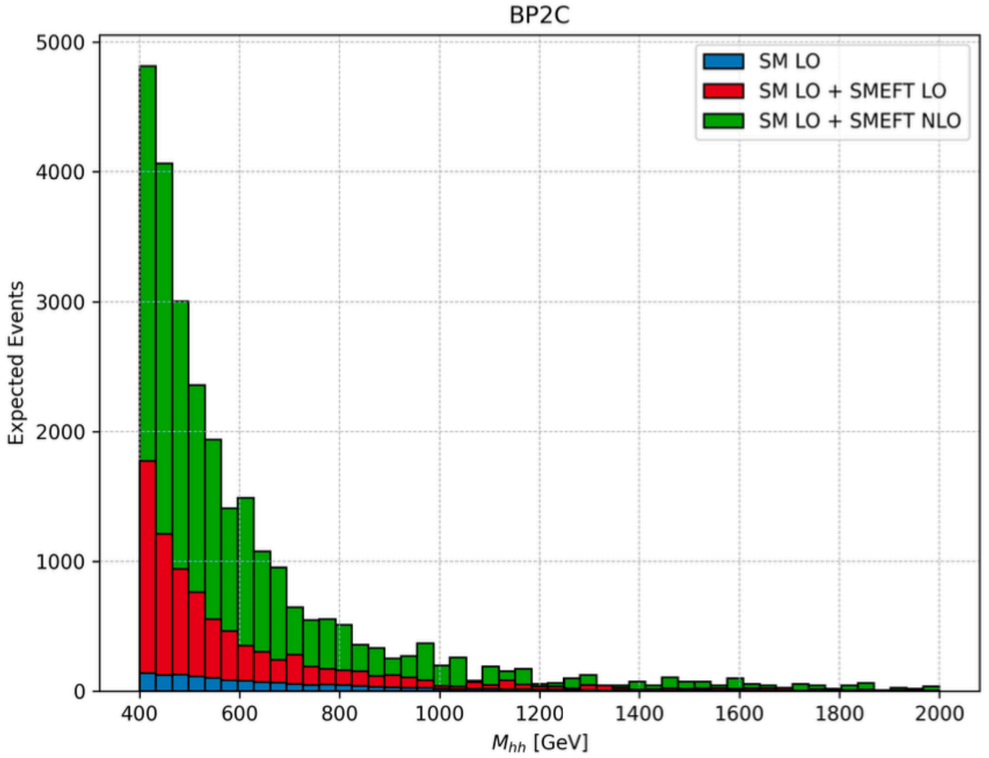
BP3			
WC		$C_{\varphi\Box}$	$C_{\varphi W}$
$\frac{C}{1\ \mathrm{TeV}^{(2)}}$	A	2	1
	B	2	-1
	C	-2	1
	D	-2	-1

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

BPs 1&2 - κ_λ domination

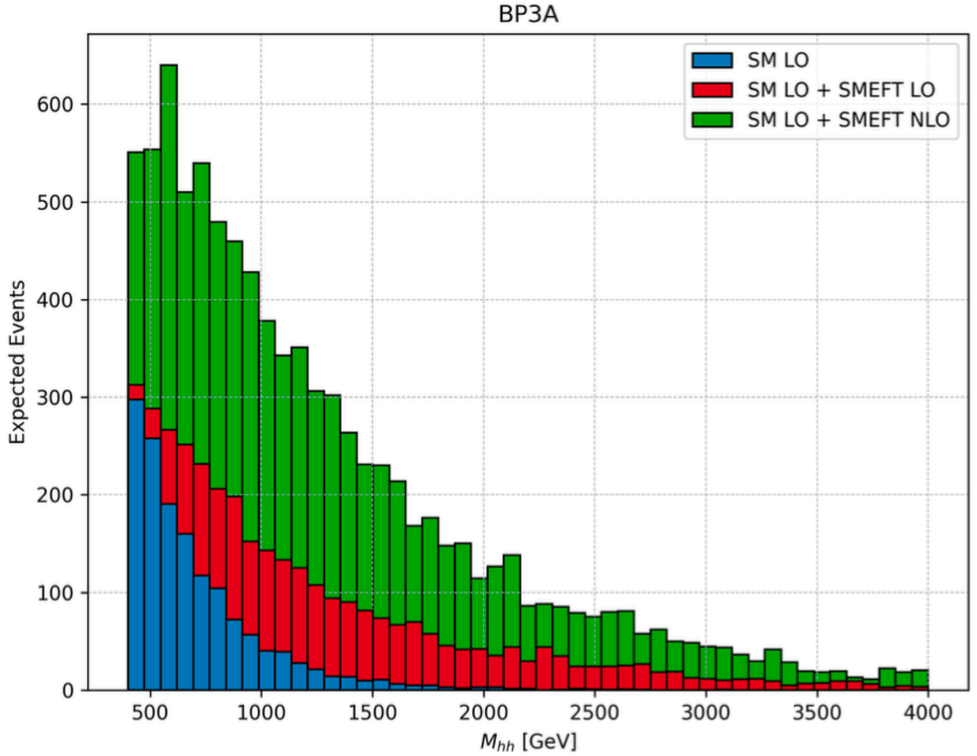


$$\frac{\sigma^{LO}_{SMEFT}}{\sigma_{SM}} = 27.69 \qquad \frac{\sigma^{NLO}_{SMEFT}}{\sigma_{SM}} = 65.02$$

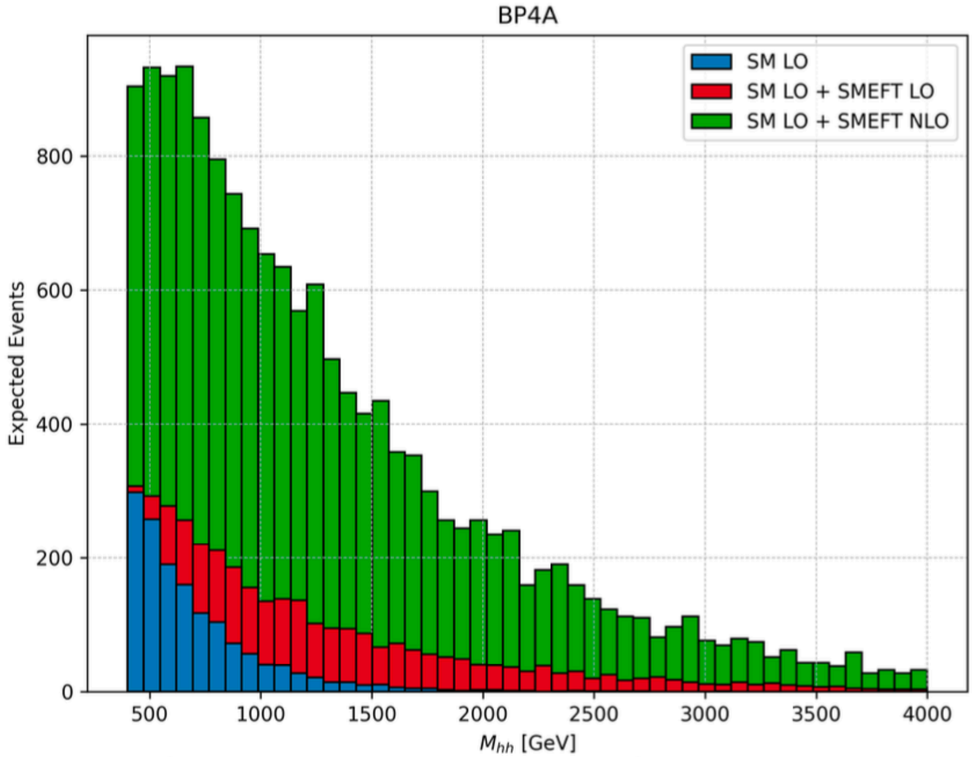


$$\frac{\sigma^{LO}_{SMEFT}}{\sigma_{SM}} = 15.13 \qquad \frac{\sigma^{NLO}_{SMEFT}}{\sigma_{SM}} = 46.08$$

BPs 3&4 - $\kappa_\lambda = 1$



$$\frac{\sigma^{LO}_{SMEFT}}{\sigma_{SM}} = 2.10 \qquad \frac{\sigma^{NLO}_{SMEFT}}{\sigma_{SM}} = 5.21$$

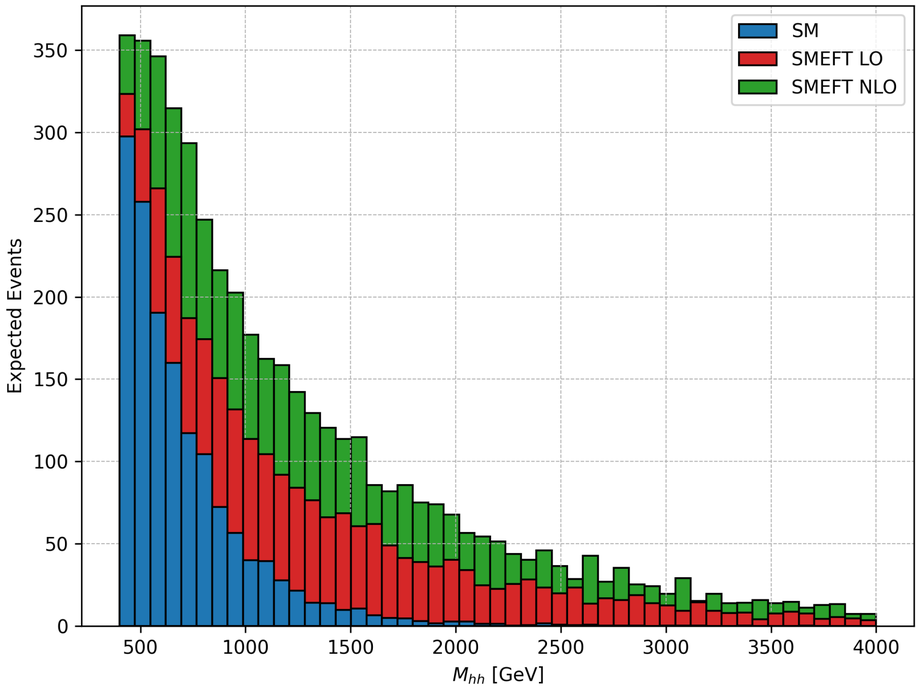


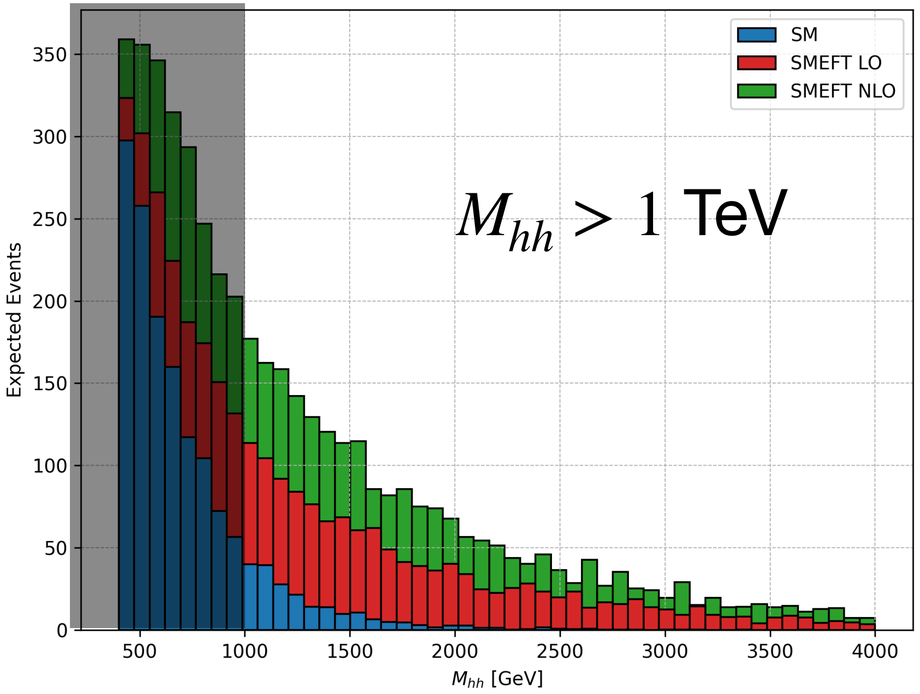
$$\frac{\sigma^{LO}_{SMEFT}}{\sigma_{SM}} = 2.10 \qquad \frac{\sigma^{NLO}_{SMEFT}}{\sigma_{SM}} = 8.87$$

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

Increasing $\Delta\sigma_{D6,8}$ ratio

$$\frac{C_{\varphi W}}{\Lambda^2} = \frac{1}{\text{TeV}^2}, \quad \sqrt{s}_{MAX} \approx 4 \text{ TeV}$$





$$\frac{\sigma^{LO}_{SMEFT}}{\sigma_{SM}} = 1.85 \quad \frac{\sigma^{NLO}_{SMEFT}}{\sigma_{SM}} = 2.72$$

$$\frac{\sigma^{LO}_{SMEFT}}{\sigma_{SM}} = 6.35 \quad \frac{\sigma^{NLO}_{SMEFT}}{\sigma_{SM}} = 11.12$$

Increasing $\Delta\sigma_{D6,8}$ ratio

- **Applying $M_{hh} > 1$ TeV cut can significantly increase $\Delta\sigma_{D6,8}$ ratio!**
- **Some more refined cuts can further improve the situation**

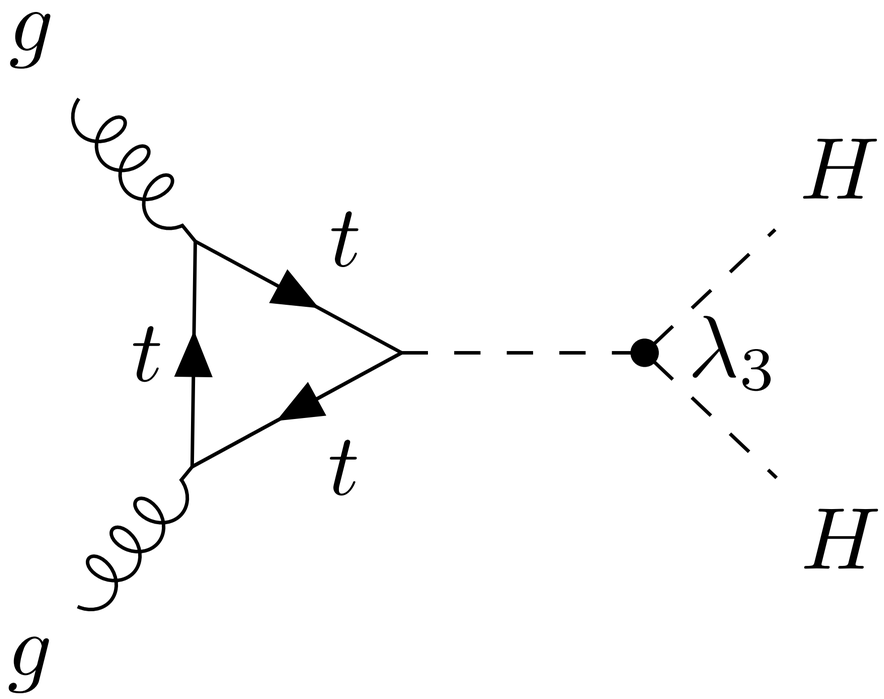
HL-LHC					
WC	$\frac{C}{1\ \text{TeV}^{2,4}}$	$\Delta\sigma_{D6}$	ΔN_{D6}	$\Delta\sigma_{D6^2+D8}$	ΔN_{D6^2+D8}
$C_{\varphi\Box}$	2	2.62	332	4.96	810
$C_{\varphi W}$	1	6.35	1095	11.12	2070
$C_{\varphi^6\Box}$	-4	-	-	1.43	88
$C^{(1)}_{W^2\varphi^4}$	-4	-	-	3.80	573
BP3 scenario A		7.92	1415	23.09	4517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

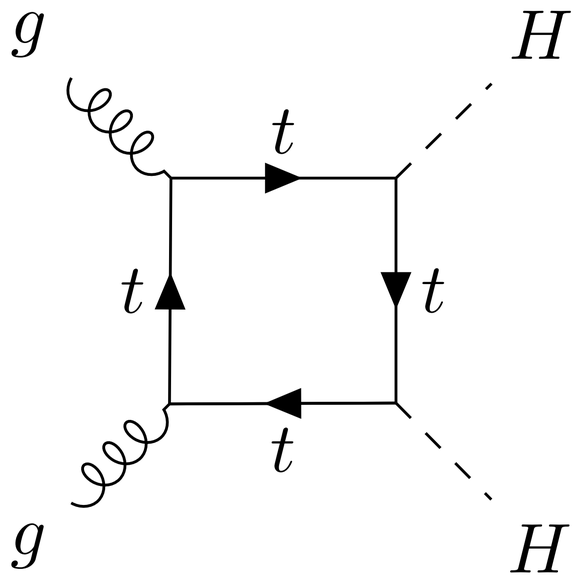
Summary

- **Study of VBF double Higgs production in SMEFT with estimation of NLO effects**
- **Combination of NDA and experimental constraints lead to estimates on dim-8 WCs**
- **Importance of dim-6^2 contributions**
- **Dim-6 and dim-6^2 dominate dim-8 contributions**
- **Value of C_i more important than s dependence**
- $\Delta\sigma_{D6,8} \propto \mathcal{O}(20)$ **(single WC) and** $\Delta\sigma_{D6,8} \propto \mathcal{O}(50)$ **(multiple WCs) for** $\kappa_\lambda \neq 1$
- $\Delta\sigma_{D6,8} \propto \mathcal{O}(3)$ **(single WC) and** $\Delta\sigma_{D6,8} \propto \mathcal{O}(10)$ **(multiple WCs) for** $\kappa_\lambda = 1$
- **Additional cuts increase** $\Delta\sigma_{D6,8}$ **ratio -> simple example for** $M_{hh} > 1$ **TeV**

Thank you!

Double Higgs production via gluon fusion





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

J. Baglio et al. 2008.11626

C_φ, C_{φ^8} and κ_λ

$$\kappa_{\lambda_3} \in [-1.2, 7.5] \quad \Rightarrow \quad \kappa_{\lambda_3} = 1 - \frac{C_\varphi}{(G_F m_h^2)(G_F \Lambda^2)} - \frac{\sqrt{2}\, C_{\varphi^8}}{(G_F m_h^2)(G_F \Lambda^2)^2}$$

C_φ only

$$-\frac{13.8}{\text{TeV}^2} \lesssim \frac{C^\varphi}{\Lambda^2} \lesssim \frac{4.7}{\text{TeV}^2}$$

Same κ_λ and enhancement!

C_φ and C_{φ^8}

$$-\frac{9.9}{\text{TeV}^2} \lesssim \frac{C_\varphi}{\Lambda^2} \lesssim \frac{3.8}{\text{TeV}^2}$$

$$-\frac{31.1}{\text{TeV}^4} \lesssim \frac{C_{\varphi^8}}{\Lambda^4} \lesssim \frac{7.4}{\text{TeV}^4}$$

$WW \to HH$
SM amplitude

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

$$\mathscr{M}_{\pm\pm}^{WW,\,SM} = \mathcal{O}\left(\frac{1}{s} \right) \qquad \mathscr{M}_{\pm\mp}^{WW,\,SM} = 2\sqrt{2} G_F M_W^2$$

$$\mathscr{M}_{0\pm}^{WW,\,SM} = \mathscr{M}_{\pm 0}^{WW,\,SM} = \mathcal{O}\left(\frac{1}{\sqrt{s}} \right)$$

$WW \to HH$

Dim-6 amplitude

$$\mathscr{M}_{00}^{WW,D6} = -3\sqrt{2}C_{\varphi}\left(\frac{1}{G_F\Lambda^2}\right) - 20C_{\varphi W}\left(\frac{M_W^2}{\Lambda^2}\right) + \frac{1}{2}(4C_{\varphi\Box} - C_{\varphi D})\left(\frac{s}{\Lambda^2}\right) - 28\sqrt{2}C_{\varphi W}^2\left(\frac{M_W^2}{\Lambda^2}\right)\left(\frac{1}{G_F\Lambda^2}\right) + \sqrt{2}(4C_{\varphi\Box}^2 + \frac{1}{4}C_{\varphi D}^2)\left(\frac{1}{G_F\Lambda^2}\right)\left(\frac{s}{\Lambda^2}\right)$$

$$\mathscr{M}_{\pm\pm}^{WW,D6} = -(4C_{\varphi\Box} - C_{\varphi D})\left(\frac{M_W^2}{\Lambda^2}\right) + 2C_{\varphi W}\left(\frac{s}{\Lambda^2}\right) - 2\sqrt{2}(4C_{\varphi\Box}^2 + \frac{1}{4}C_{\varphi D}^2)\left(\frac{M_W^2}{\Lambda^2}\right)\left(\frac{1}{G_F\Lambda^2}\right) + 6\sqrt{2}C_{\varphi W}^2\left(\frac{1}{G_F\Lambda^2}\right)\left(\frac{s}{\Lambda^2}\right)$$

$$\mathscr{M}_{\pm\mp}^{WW,D6} = (4C_{\varphi\Box} - C_{\varphi D})\left(\frac{M_W^2}{\Lambda^2}\right) + \sqrt{2}(4C_{\varphi\Box}^2 + \frac{1}{4}C_{\varphi D}^2)\left(\frac{M_W^2}{\Lambda^2}\right)\left(\frac{1}{G_F\Lambda^2}\right) + 2\sqrt{2}C_{\varphi W}^2\left(\frac{1}{G_F\Lambda^2}\right)\left(\frac{s}{\Lambda^2}\right)$$

$$\mathscr{M}_{0\pm}^{WW,D6} = -4\sqrt{2}\cot\theta C_{\varphi W}\left(\frac{\sqrt{s}M_W}{\Lambda^2}\right) - 8C_{\varphi W}^2\cot\theta\left(\frac{1}{G_F\Lambda^2}\right)\left(\frac{\sqrt{s}M_W}{\Lambda^2}\right)$$

$WW \to HH$

Dim-8 amplitude #1

$$\mathscr{M}_{00}^{WW,D8} = -6C_{\varphi^8}\left(\frac{1}{G_F\Lambda}\right)^2 + \frac{\sqrt{2}}{4}\left(8C_{\varphi^6\Box} - C_{\varphi^6 D^2}\right)\left(\frac{s}{\Lambda^2}\right)\left(\frac{1}{G_F\Lambda^2}\right) - \frac{1}{8}\left[\left(C^{(1)}_{\varphi^4 D^4} + C^{(2)}_{\varphi^4 D^4} + 4\,C^{(3)}_{\varphi^4 D^4}\right) + \left(C^{(1)}_{\varphi^4 D^4} + C^{(2)}_{\varphi^4 D^4}\right)\cos^2\theta\right]\left(\frac{s}{\Lambda^2}\right)^2$$

$$\mathscr{M}_{\pm\pm}^{WW,D8} = 12\,C_{\varphi^8}\left(\frac{M_W^2}{s}\right)\left(\frac{1}{G_F\Lambda^2}\right)^2 - \frac{1}{\sqrt{2}}\left(8\,C_{\varphi^6\Box} - C_{\varphi^6 D^2}\right)\left(\frac{M_W^2}{\Lambda^2}\right)\left(\frac{1}{G_F\Lambda^2}\right) + \frac{1}{4}\left[4\,C^{(3)}_{\varphi^4 D^4} + \left(C^{(1)}_{\varphi^4 D^4} + C^{(2)}_{\varphi^4 D^4}\right)\sin^2\theta\right]\left(\frac{M_W^2}{\Lambda^2}\right)\left(\frac{s}{\Lambda^2}\right)$$

$$\mathscr{M}_{\pm\mp}^{WW,D8} = +\frac{\sqrt{2}}{4}\left(8C_{\varphi^6\Box} - C_{\varphi^6 D^2}\right)\left(\frac{M_Z^2}{\Lambda^2}\right)\left(\frac{1}{G_F\Lambda^2}\right) + \frac{1}{4}\left(C^{(1)}_{\varphi^4 D^4} + C^{(2)}_{\varphi^4 D^4}\right)\sin^2\theta\left(\frac{M_W^2}{\Lambda^2}\right)\left(\frac{s}{\Lambda^2}\right)$$

$$\mathscr{M}_{0\pm}^{WW,D8} = +\frac{1}{8\sqrt{2}}\left(C^{(1)}_{\varphi^4 D^4} + C^{(2)}_{\varphi^4 D^4}\right)\sin 2\theta\left(\frac{s^{3/2}M_W}{\Lambda^4}\right)$$

$WW \to HH$

Dim-8 amplitude #2

$$\mathscr{M}_{00}^{WW,D8} = + \left[\frac{1}{2} C_{W^2\varphi^2 D^2}^{(1)} (\sin^2\theta + 1) + 2 C_{W^2\varphi^2 D^2}^{(2)}\right] \left(\frac{M_W^2}{\Lambda^2}\right) \left(\frac{s}{\Lambda^2}\right) - 14\sqrt{2} C_{W^2\varphi^4}^{(1)} \left(\frac{M_W^2}{\Lambda^2}\right) \left(\frac{1}{G_F \Lambda^2}\right)$$

$$\mathscr{M}_{\pm\pm}^{WW,D8} = - \left(\frac{1}{4} C_{W^2\varphi^2 D^2}^{(1)} + C_{W^2\varphi^2 D^2}^{(2)}\right) \left(\frac{s^2}{\Lambda^4}\right) + 3\sqrt{2} C_{W^2\varphi^4}^{(1)} \left(\frac{1}{G_F \Lambda^2}\right) \left(\frac{s}{\Lambda^2}\right)$$

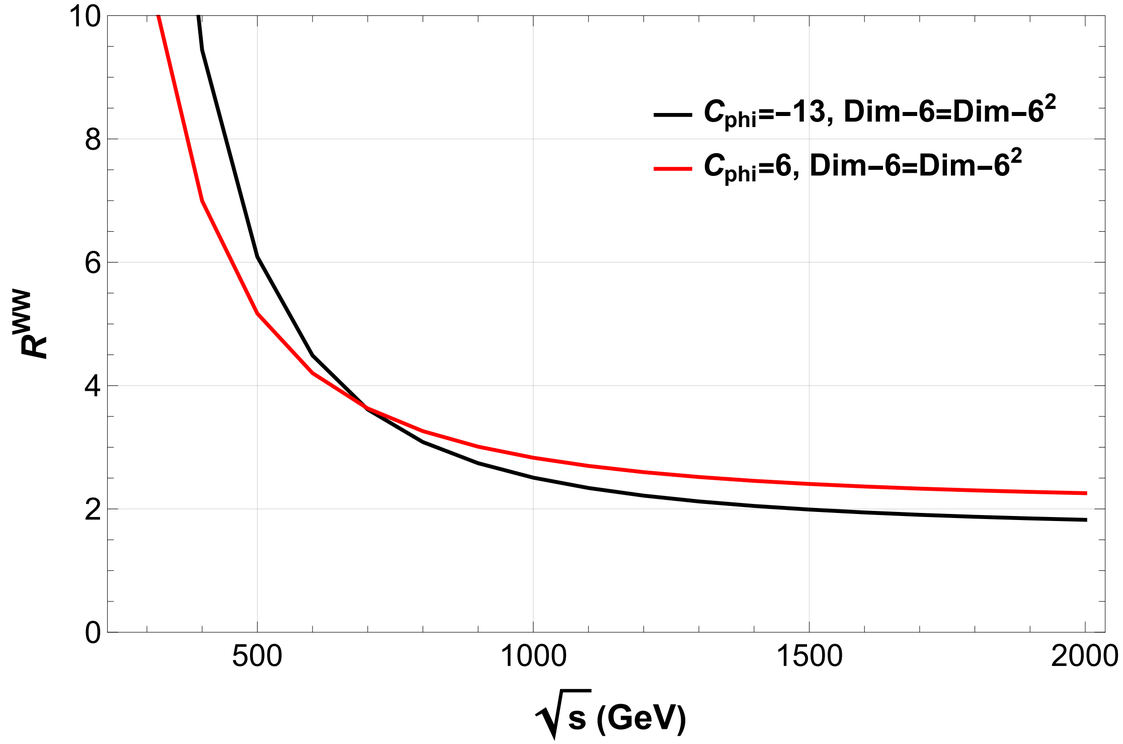
$$\mathscr{M}_{\pm\mp}^{WW,D8} = - \frac{1}{8} \sin^2\theta C_{W^2\varphi^2 D^2}^{(1)} \left(\frac{s^2}{\Lambda^4}\right)$$

$$\mathscr{M}_{0\pm}^{WW,D8} = - 4 C_{W^2\varphi^4}^{(1)} \cot\theta \left(\frac{s^{1/2} M_W}{\Lambda^2}\right) \left(\frac{1}{G_F \Lambda^2}\right) - \frac{1}{8\sqrt{2}} C_{W^2\varphi^2 D^2}^{(1)} \sin 2\theta \left(\frac{s^{3/2} M_W}{\Lambda^4}\right)$$

$WW \to HH$

Dim-6 cross-section enhancement #1

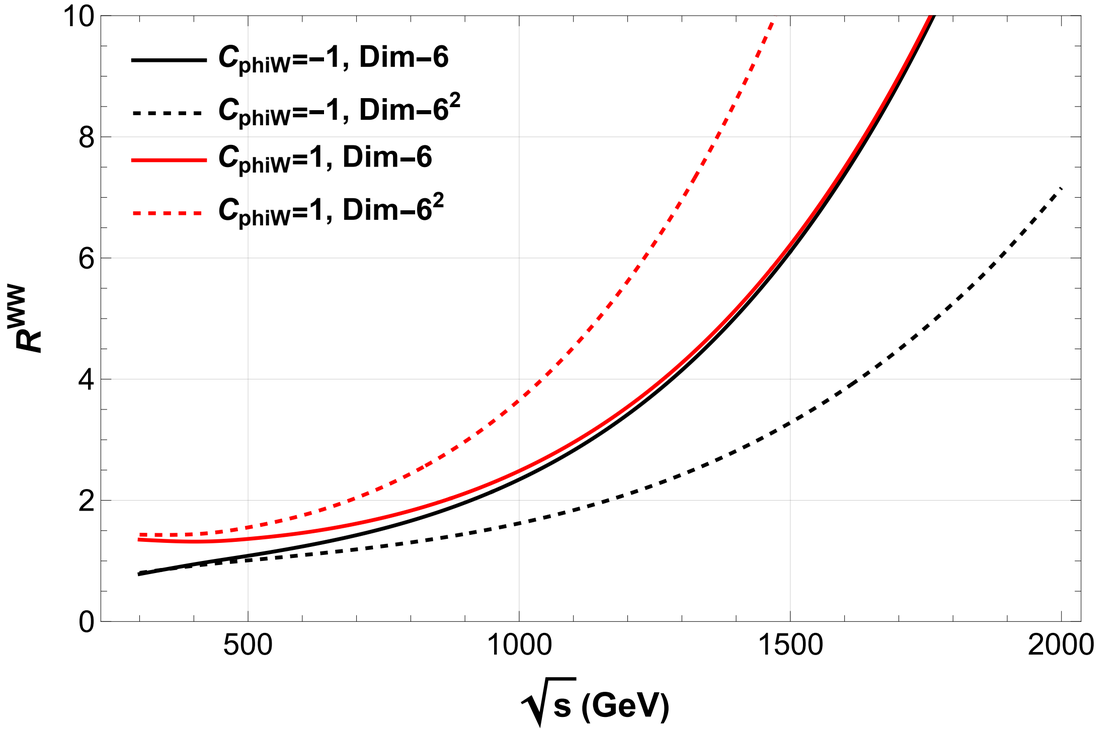
$$R^{VV} = \frac{\sigma_{SMEFT}(VV \to HH)}{\sigma_{SM}(VV \to HH)}$$

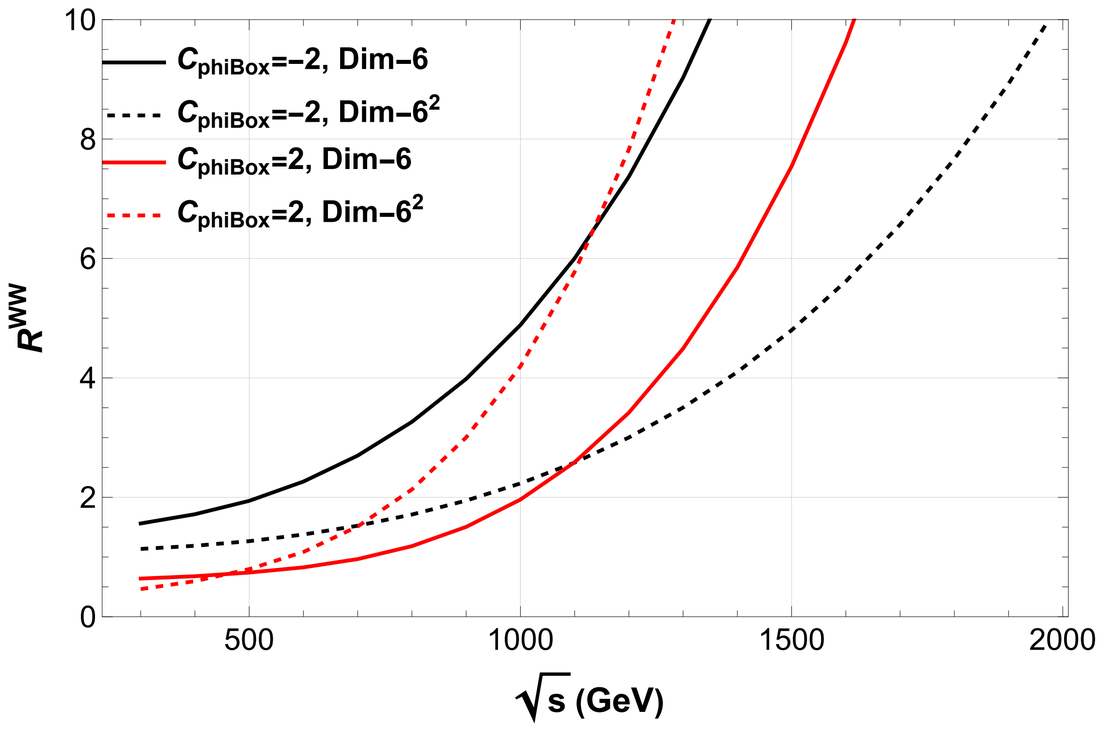


$$\mathscr{M} \propto 1$$

$WW \to HH$

Dim-6 cross-section enhancement #2

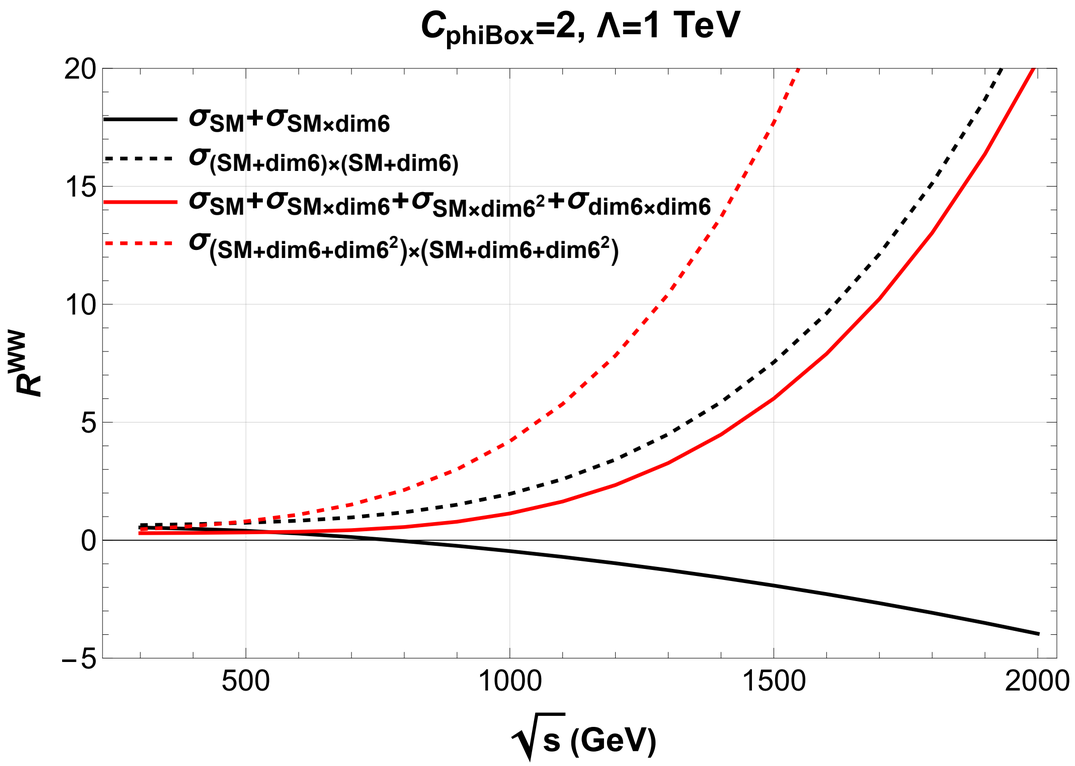


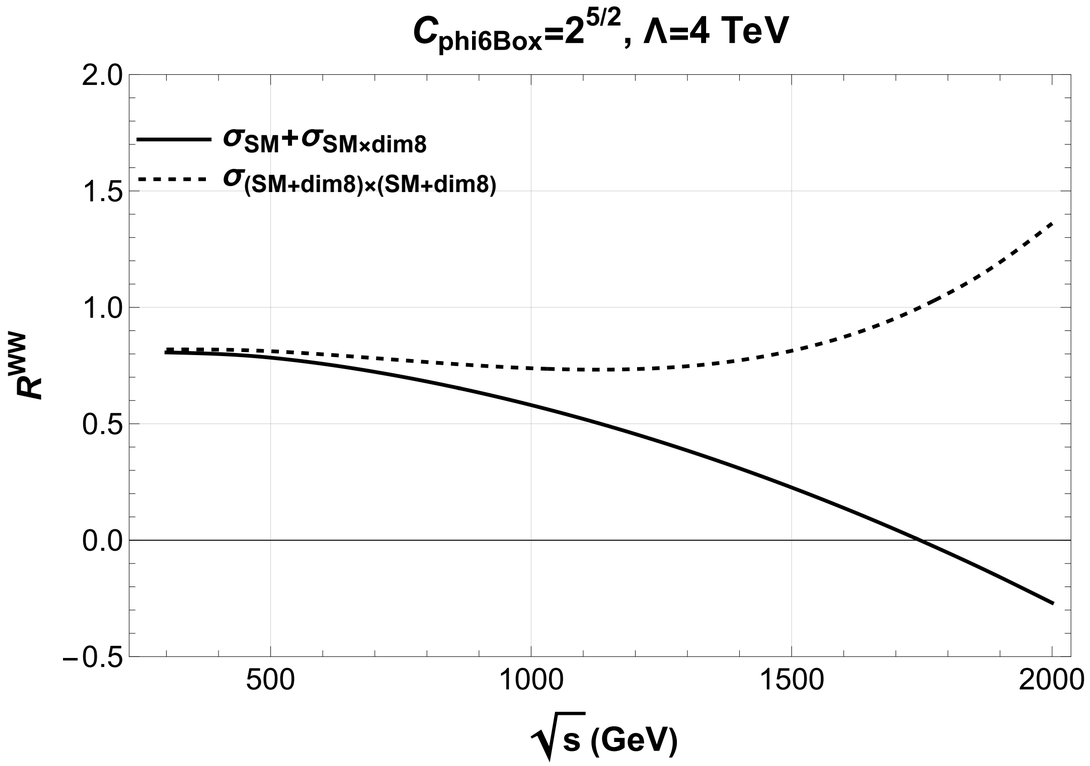


$$\mathscr{M} \propto s$$

The amplitude and EFT truncation

$$\sigma \propto (\mathscr{M}_{SM} + \mathscr{M}_{dim-6} + \mathscr{M}_{dim-6^2} + \mathscr{M}_{dim-8}) \times (\mathscr{M}_{SM} + \mathscr{M}_{dim-6} + \mathscr{M}_{dim-6^2} + \mathscr{M}_{dim-8})$$

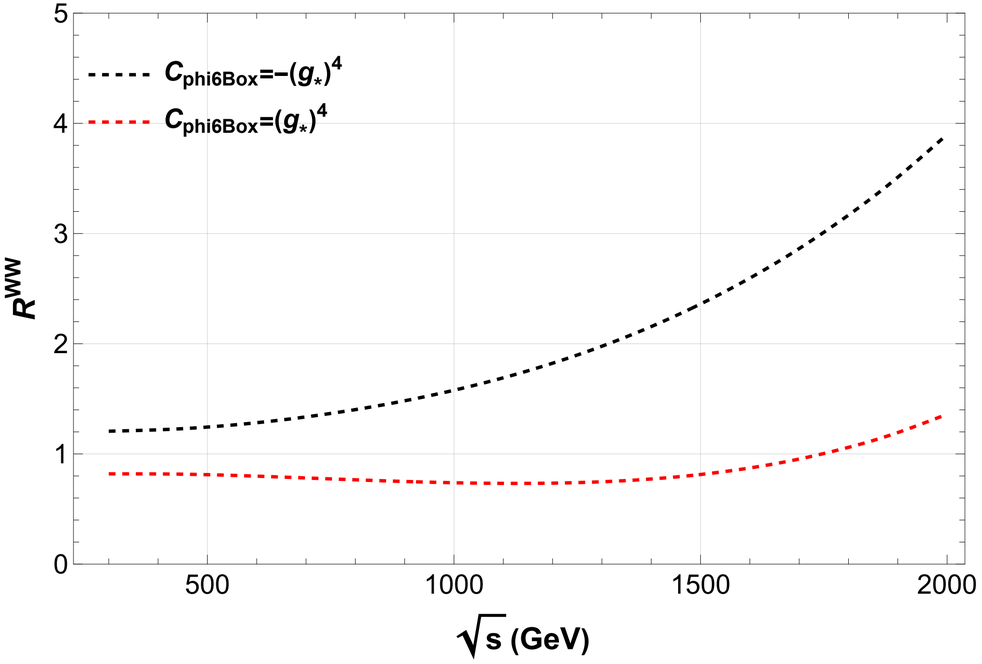




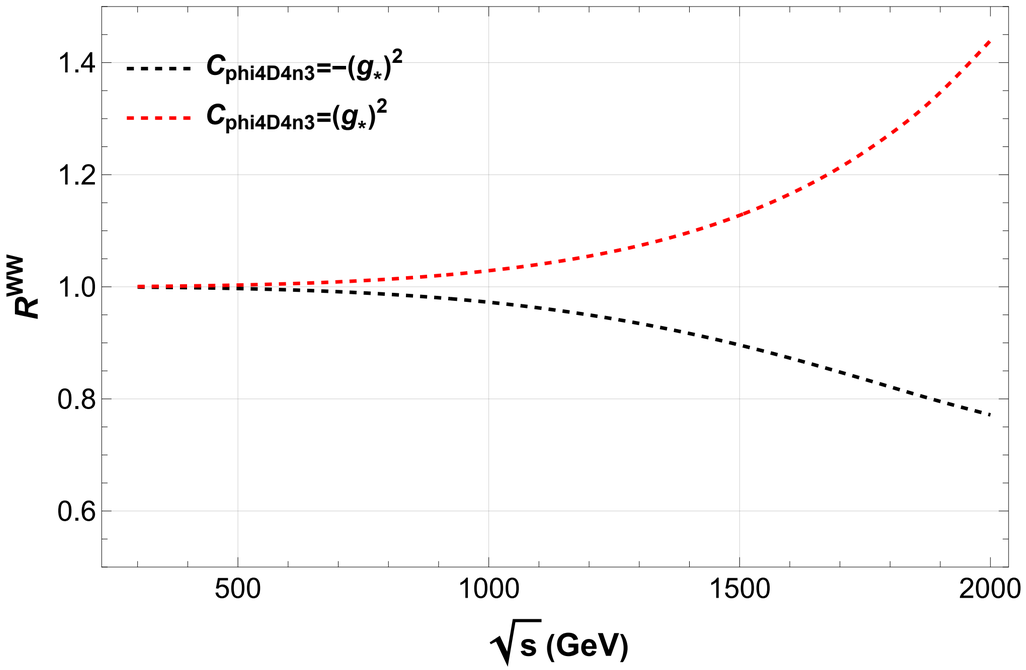
$WW \to HH$

Dim-8 cross-section enhancement #1

$$g_* = 4\sqrt{2},\ \Lambda = 4\ \text{TeV}$$



$\mathscr{M} \propto s$

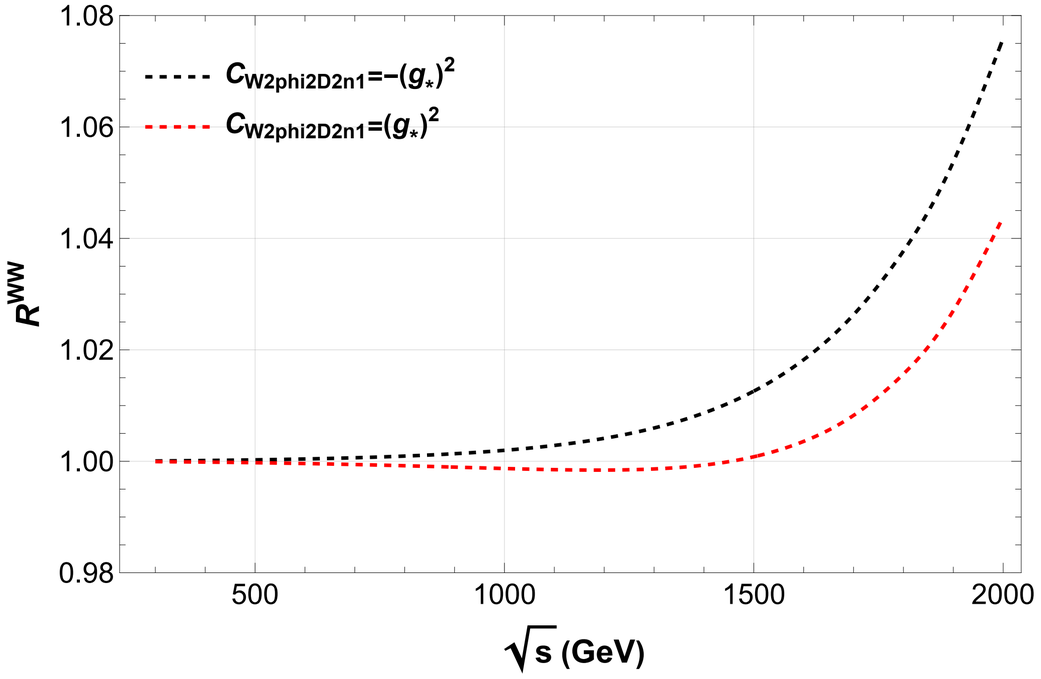


$\mathscr{M} \propto s^2$

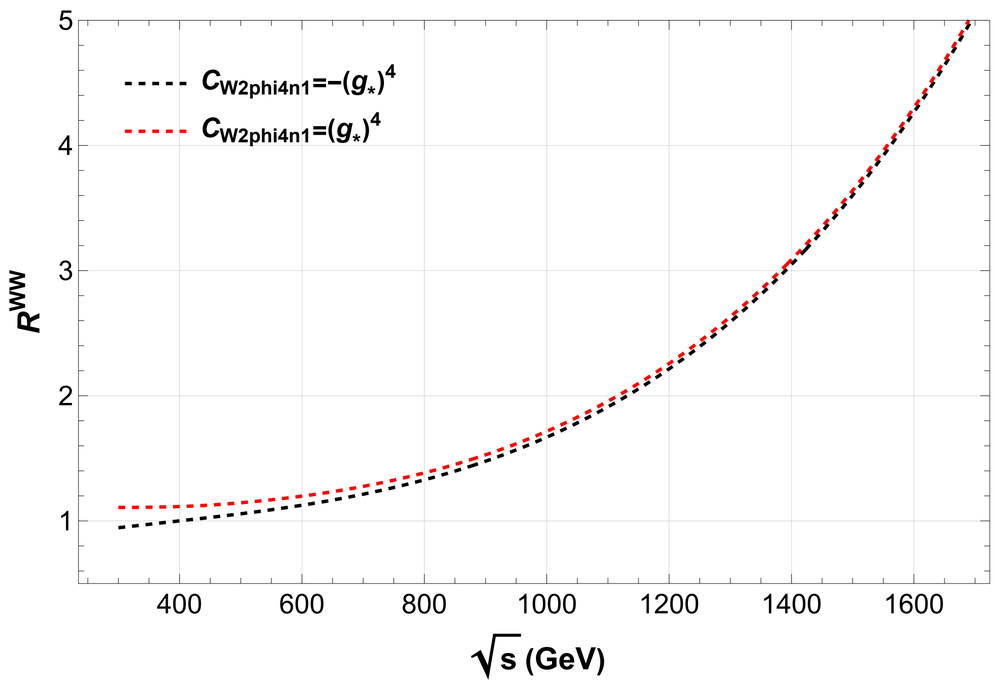
$WW \to HH$

Dim-8 cross-section enhancement #2

$$g_* = 4\sqrt{2},\ \Lambda = 4\ \text{TeV}$$



$\mathscr{M} \propto s^2$



$\mathscr{M} \propto s$

g_* and theoretical consistency

- Loop expansion criterion, unitarity bounds, positivity bounds, expansion validity
  E. S. Almeida et al. 2004.05174, S. Mahmud K. Tobioka 2501.16439, …

- For $\sqrt{s} = M_{hh} \approx 2$ TeV we can assume

$$g_* \leq min\left(\sqrt{2}\frac{\Lambda}{1\ \text{TeV}}, 4\pi\right)$$

- EFT validity

$$\frac{s_{MAX}}{\Lambda^2} < 1$$