Multiple Higgs and gauge boson production beyond the SM

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Multiparticle production is the hallmark of strongly coupled models

Take a nonlinear sigma model:

$$\mathcal{L}_{NL\sigma M} = \frac{v^2}{4} \mathrm{Tr}\left[\partial_\mu U \partial^\mu U^\dagger\right]$$

The cross section to produce n relativistic pions is:

$$\sigma(2 \to n) \sim \frac{1}{s}\left(\frac{s}{v^n}\right)^2 s^{n-2}$$

The cross section grows faster with number of pions: violates perturbative unitarity.

In the SM there must be strong cancellations in the scattering amplitudes to avoid unitarity violation:

$$\mathcal{M}(2 \to 2) : s \Longrightarrow \mathrm{const}$$

$$\mathcal{M}(2 \to 4) : s \Longrightarrow 1/s$$

In composite Higgs models the unitarization is only partial due to anomalous Higgs couplings.

One can have greater sensitivity to modifications of Higgs couplings in multi-particle production.

Can parametrize anomalous couplings with an effective lagrangian (à la SILH):

$$\mathcal{L}_{\rm eff} = \frac{v^2}{4}\left(1 + 2a\frac{h}{v} + b\frac{h^2}{v^2} + b_3\frac{h^3}{v^3} + \cdots\right) \mathrm{Tr}\left[\partial_\mu U \partial^\mu U^\dagger\right]$$
$$+ \frac{1}{2}(\partial_\mu h)^2 - \frac{1}{2}m_h^2 h^2 - d_3 \lambda v h^3 - d_4 \frac{\lambda}{4} h^4 + \cdots$$

SM values $a = b = d_3 = d_4 = 1$ and $b_3 = 0$

$$a = \sqrt{1-\xi},\ b = (1-2\xi)\ \cdots$$

$$\mathcal{M}_{00;+-} = \frac{s\left[(1-a^2)s - m_h^2\right]}{v^2(s-m_h^2)} \underset{s \gg m_h^2}{\longrightarrow} (1-a^2)\frac{s}{v^2}$$

Amazing cancellations in the SM

$$\mathcal{M}_{00;00+-} \propto \tfrac{1}{v^4}\,[72s\,(13a^4 - a^2(7b+5) - 1) +$$
$$3m_h^2\,(1580a^4 - 378a^3d_3 - 3a^2(245b+131) - 74) +$$
$$\tfrac{m_h^4}{s}\,(9774a^4 - 3087a^3d_3 - a^2(4494b+1289) + 52) +$$
$$\cdots] \tag{14}$$

It grows with s, as expected. However, in the SM ($a = b = d_3 = 1$) one obtains in the limit $s \gg m_h^2$:

$$\mathcal{M}_{00;00+-} \propto \frac{1}{s}\frac{m_h^4}{v^4} \tag{15}$$

Expect a huge enhancement in 2➔4 with anomalous couplings! Amplitude goes as s instead of 1/s.

Huge enhancements

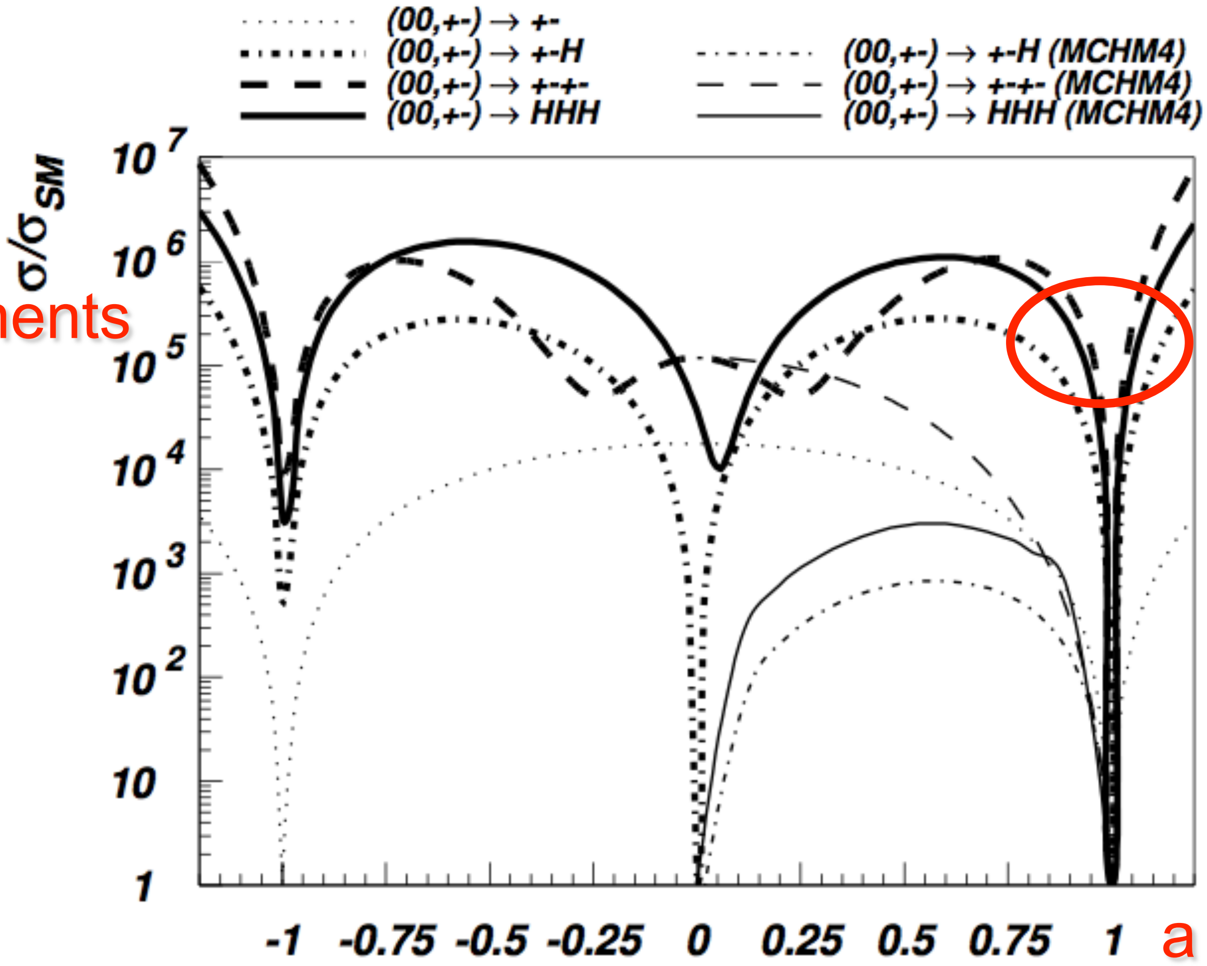


Figure 1: Ratio of the SMEFF (thin lines) and MCHM4 (thick lines) cross sections to the SM one versus a parameter at a fixed energy of $\sqrt{s} = 2$ TeV. The different channels are: $(00,+-) \to +-+-$ (dashed line), $(00,+-) \to +-h$ (dot-dashed line), $(00,+-) \to hhhh$ (solid line), and $(00,+-) \to +-$ (dotted line) for comparison. The notation $(00,+-)$ indicates that both 00 and $+-$ initial states were taken into account.

For MCHM there is a h to –h symmetry that reduces the enhancement

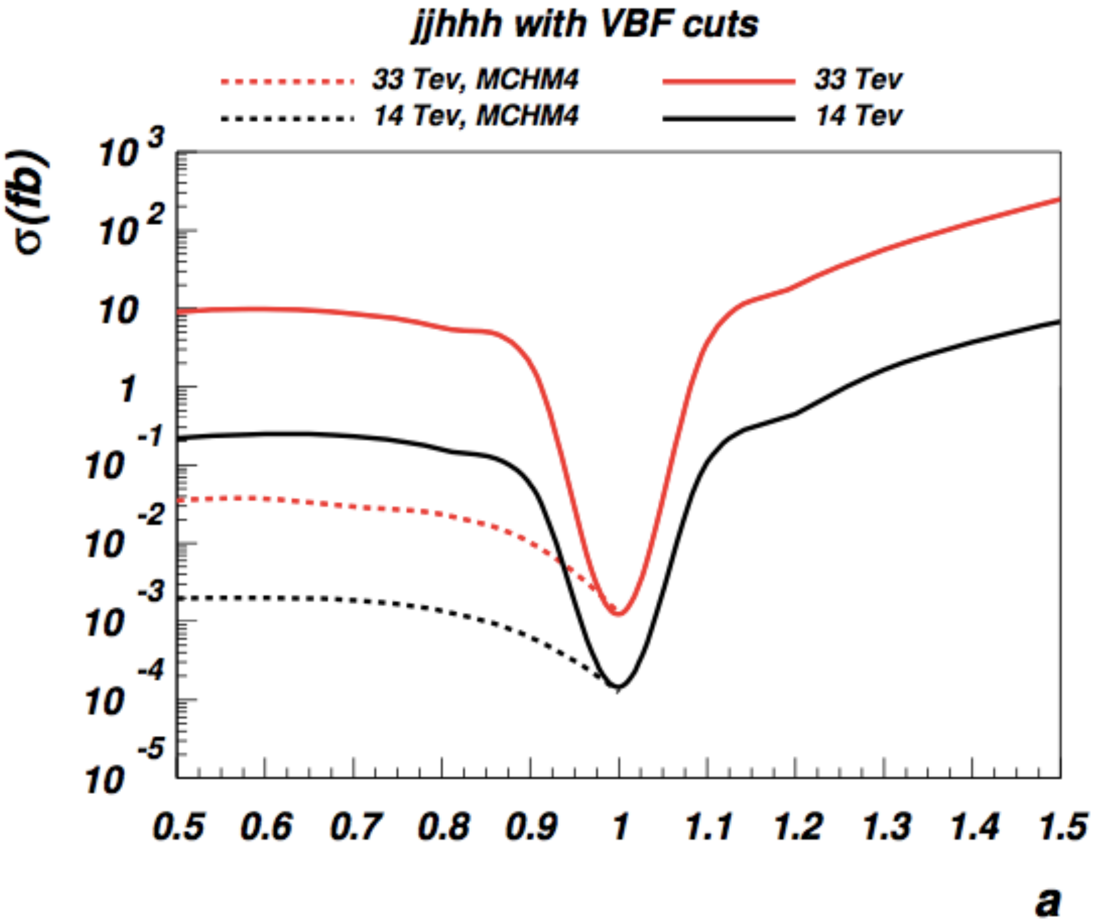
Do large enhancements persist in full calculation?

Yes, in triple higgs production!

Process	14 TeV with (without) VBF cuts		33 TeV with (without) VBF cuts	
	a=1.0 b=1.0	a=0.9 b=1.0	a=1.0 b=1.0	a=0.9 b=1.0
$pp \to jjW^+W^-$	95.2 (1820)	99.3 (1700)	512 (5120)	540 (5790)
$pp \to jjW^+W^-h$	0.011 (0.206)	0.0088 (0.172)	0.0765 (0.914)	0.0626 (0.758)
$pp \to jjhhh$	1.16×10^{-4} (3.01×10^{-4})	0.0566 (0.0613)	0.00115 (0.00165)	1.85 (1.46)

Table 2: Cross section (in fb) for $pp \to jjW^+W^-$, $pp \to jjW^+W^-h$ and $pp \to jjhhh$ processes evaluated with Madgraph5.

Triple higgs production



Too small to be seen...