VECTOR BOSON FUSION AND VECTOR BOSON SCATTERING

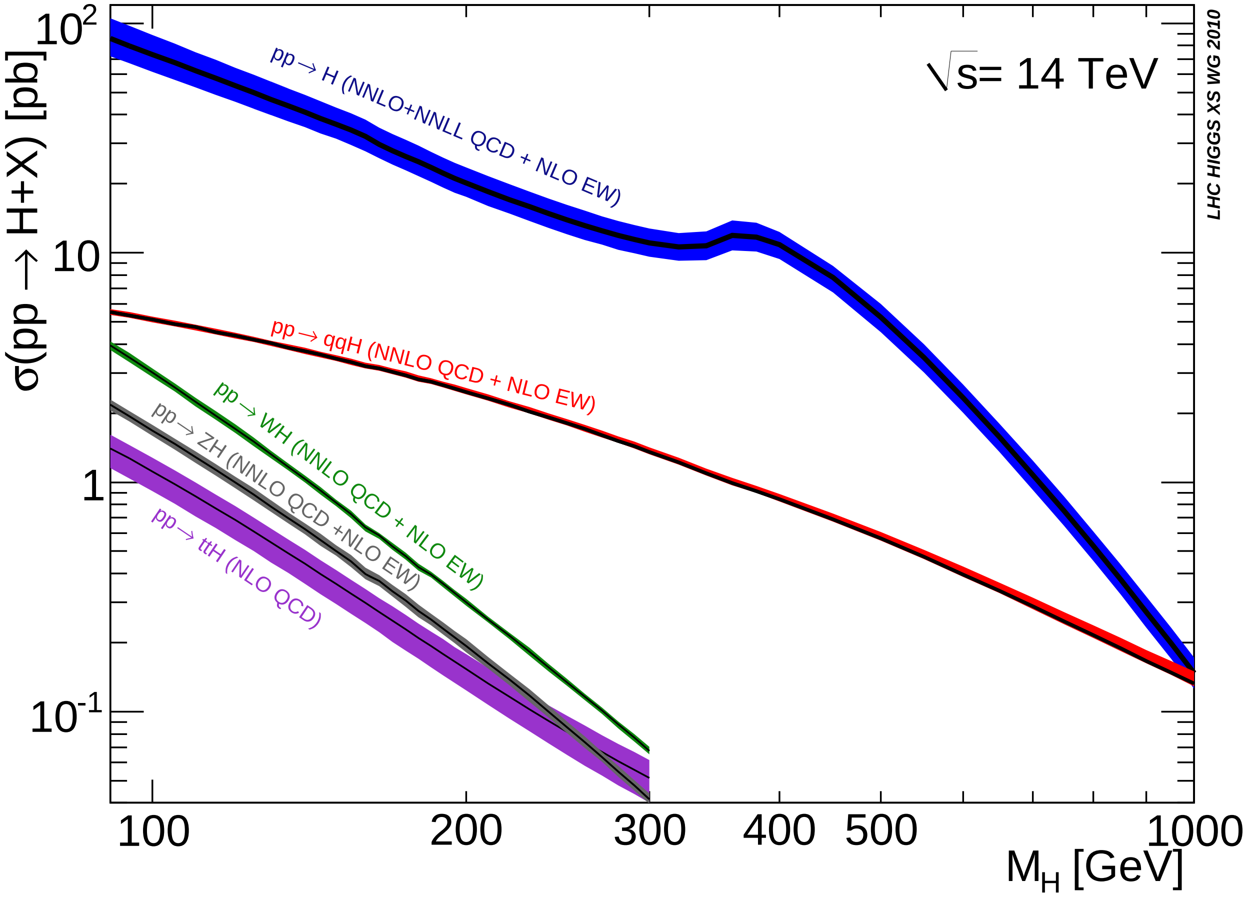
Dieter Zeppenfeld

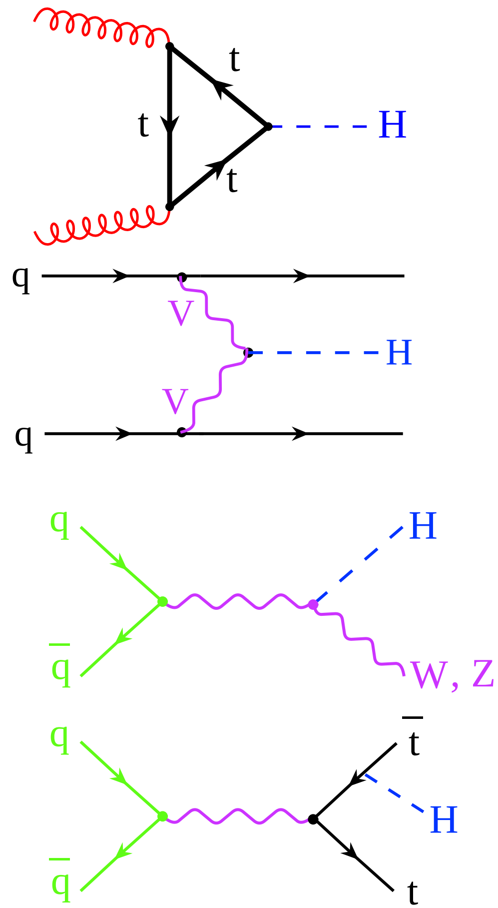
Karlsruhe Institute of Technology

LHC Higgs cross section workshop, CERN, June 12-13, 2014

- Higgs coupling measurement and VBF
- Effective Lagrangians and anomalous couplings
- $VVVV$ vertices and VBS

Total cross sections at the LHC



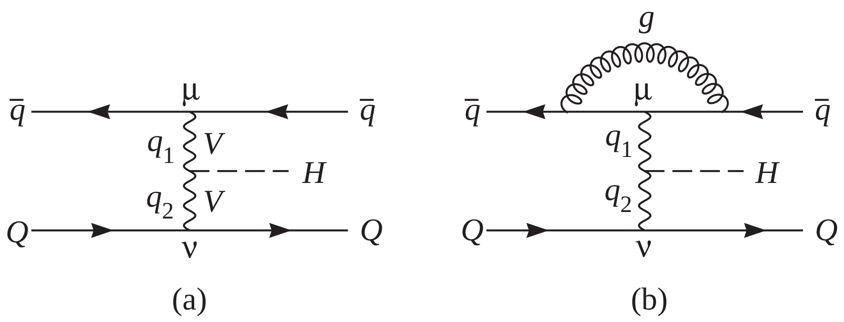


Advantages of Higgs production via VBF

- Theoretical uncertainties for VBF are particularly small
- Measurments of couplings in VBF will be limited by statistics and background systematics
- VBF is best single channel for $h \to \tau\tau$ measurements
- Signal strengths for $h \to \gamma\gamma$ and $h \to VV$ in VBF measure κ_V^4/Γ_{tot}
  $\Longrightarrow$ important ingredient for disentangling Higgs couplings
- VBF production and $H \to ZZ \to llll$ will be important to measure the tensor structure of the HVV vertex

Tensor structure of the HVV coupling

Most general HVV vertex $T^{\mu\nu}(q_1, q_2)$



$$
\begin{aligned}
T^{\mu\nu} &= a_1\, g^{\mu\nu} + \\
&\quad a_2\, \left(q_1 \cdot q_2\, g^{\mu\nu} - q_1^{\nu} q_2^{\mu}\right) + \\
&\quad a_3\, \varepsilon^{\mu\nu\rho\sigma}\, q_{1\rho} q_{2\sigma}
\end{aligned}
$$

The $a_i = a_i(q_1, q_2)$ are scalar form factors

Physical interpretation of terms:

SM Higgs $\quad \mathcal{L}_I \sim H V_\mu V^\mu \longrightarrow a_1$

loop induced couplings for neutral scalar

CP even $\quad \mathcal{L}_{eff} \sim H V_{\mu\nu} V^{\mu\nu} \longrightarrow a_2$

CP odd $\quad \mathcal{L}_{eff} \sim H V_{\mu\nu} \tilde{V}^{\mu\nu} \longrightarrow a_3$

Must distinguish a_1, a_2, a_3 experimentally

Connection to effective Lagrangian

We need model of the underlying UV physics to determine the form factors $a_i(q_1, q_2)$

Approximate its low-energy effects by an effective Lagrangian

$$\mathcal{L}_{\mathrm{eff}} = \frac{f_{WW}}{\Lambda^2} \phi^\dagger \hat{W}_{\mu\nu} \hat{W}^{\mu\nu} \phi + \frac{f_\phi}{\Lambda^2} \left(\phi^\dagger \phi - \frac{v^2}{2} \right) (D_\mu \phi)^\dagger D^\mu \phi + \cdots + \sum_i \frac{f_i^{(8)}}{\Lambda^4} \mathcal{O}_i^{(8)} + \cdots$$

Gives leading terms for form factors, e.g. for hWW coupling

$$a_1 = \frac{2m_W^2}{v} \left(1 + \frac{f_\phi}{\Lambda^2} \frac{v^2}{2} \right) + \sum_i c_i^{(1)} \frac{f_i^{(8)}}{\Lambda^4} v^2 q^2 + \cdots$$

$$a_2 = c^{(2)} \frac{f_{WW}}{\Lambda^2} v + \sum_i c_i^{(2)} \frac{f_i^{(8)}}{\Lambda^4} v q^2 + \cdots$$

$$a_3 = c^{(3)} \frac{\tilde{f}_{WW}}{\Lambda^2} v + \sum_i c_i^{(3)} \frac{\tilde{f}_i^{(8)}}{\Lambda^4} v q^2 + \cdots$$

Describe same physics (for a particular vertex) by taking some minimal set of effective Lagrangian coefficients f_i as form factors

Implementation in VBFNLO

Start from effective Lagrangians (set PARAMETR1=.true. in anom_HVV.dat)

$$\mathcal{L} = \frac{g_{5e}^{HZZ}}{2\Lambda_5} H Z_{\mu\nu} Z^{\mu\nu} + \frac{g_{5o}^{HZZ}}{2\Lambda_5} H \tilde{Z}_{\mu\nu} Z^{\mu\nu} + \frac{g_{5e}^{HWW}}{\Lambda_5} H W^+_{\mu\nu} W^{\mu\nu}_- + \frac{g_{5o}^{HWW}}{\Lambda_5} H \tilde{W}^+_{\mu\nu} W^{\mu\nu}_- +$$
$$\frac{g_{5e}^{HZ\gamma}}{\Lambda_5} H Z_{\mu\nu} A^{\mu\nu} + \frac{g_{5o}^{HZ\gamma}}{\Lambda_5} H \tilde{Z}_{\mu\nu} A^{\mu\nu} + \frac{g_{5e}^{H\gamma\gamma}}{2\Lambda_5} H A_{\mu\nu} A^{\mu\nu} + \frac{g_{5o}^{H\gamma\gamma}}{2\Lambda_5} H \tilde{A}_{\mu\nu} A^{\mu\nu}$$

or , alternatively, (set PARAMETR3=.true. in anom_HVV.dat)

$$\mathcal{L}_{\mathrm{eff}} = \frac{f_{WW}}{\Lambda_6^2} \phi^\dagger \hat{W}_{\mu\nu} \hat{W}^{\mu\nu} \phi + \frac{f_{BB}}{\Lambda_6^2} \phi^\dagger \hat{B}_{\mu\nu} \hat{B}^{\mu\nu} \phi + \text{ CP-odd part} + \cdots$$

see VBFNLO manual for details on how to set the anomalous coupling choices

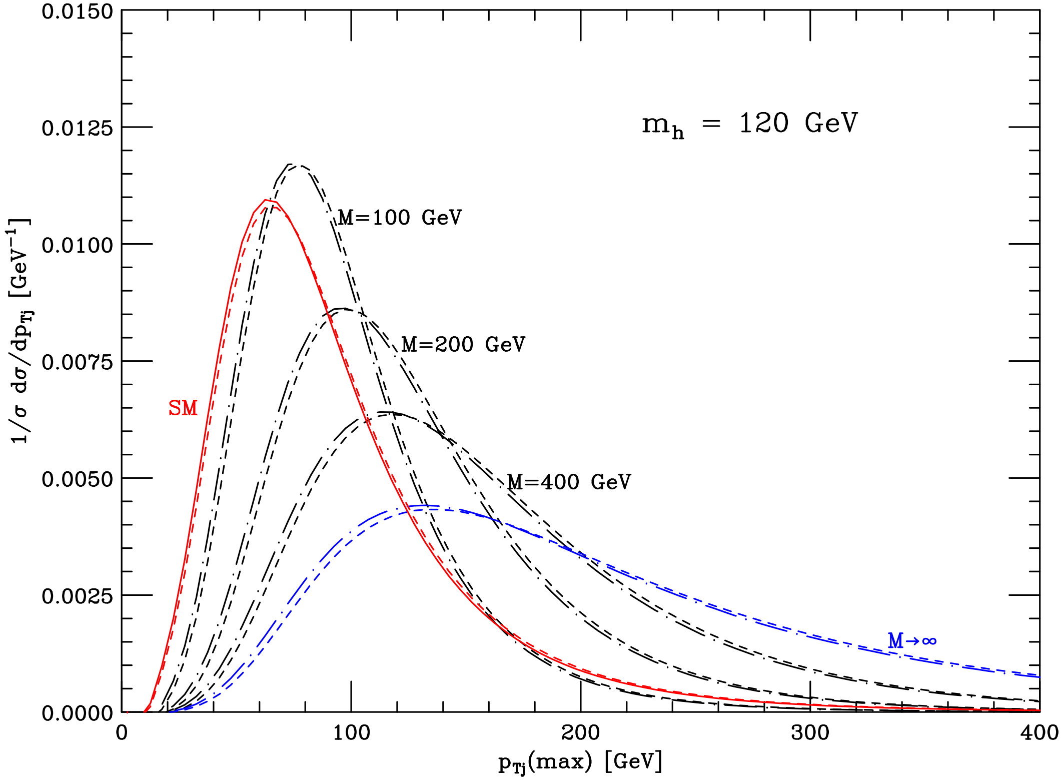
Remember to choose form factors in anom_HVV.dat

$$F_1 = \frac{M^2}{q_1^2 - M^2} \frac{M^2}{q_2^2 - M^2} \qquad \text{or} \qquad F_2 = -2\, M^2\, C_0\left(q_1^2, q_2^2, (q_1+q_2)^2, M^2\right)$$

Jet transverse momentum

Form factors affect momentum transfer and thus jet transverse momenta (Here: a_2 only)

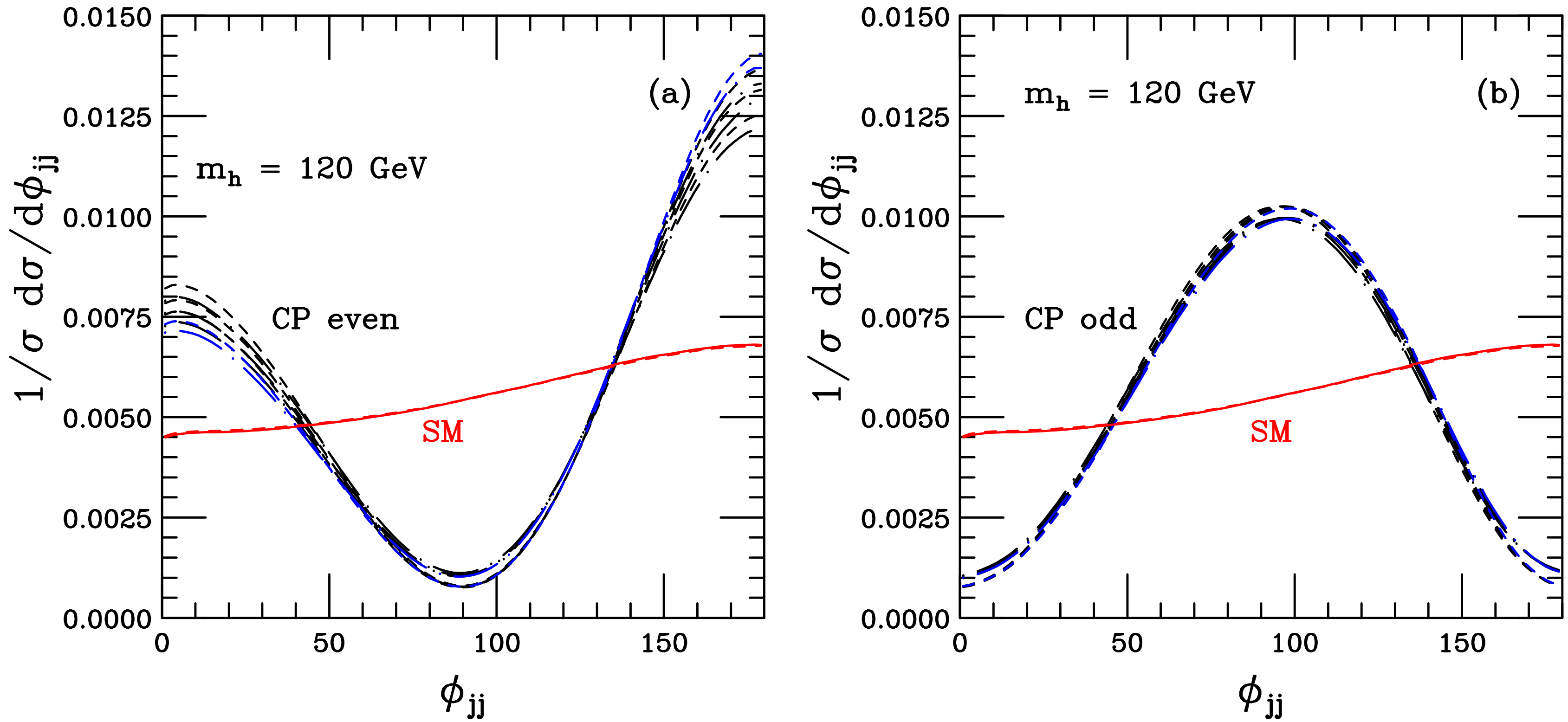
Figy, DZ hep-ph/0403297



- Change in tagging jet p_T distributions is sensitive indicator of anomalous couplings
- Can choose form-factor such as to approximate SM p_T distributions of the two tagging jets

Azimuthal angle correlations

Tell-tale signal for non-SM coupling is azimuthal angle between tagging jets



Dip structure at 90° (CP even) or 0/180° (CP odd) only depends on tensor structure of hVV vertex. Very little dependence on form factor, LO vs. NLO, Higgs mass etc.

Same physics in decay plane correlations for $h \to ZZ^* \to 4$ leptons

Vector boson scattering

The $m_h = 126$ GeV Higgs will unitarize $VV \to VV$ scattering provided it has SM hVV couplings

$\Longrightarrow$ Check this by either

- precise measurements of the hVV couplings at the light Higgs resonance
- measurement of $VV \to VV$ differential cross sections at high p_T and invariant mass

Full $qq \to qqVV$ with VV leptonic and semileptonic decay is implemented in VBFNLO with NLO QCD corrections and large set of dimension 6 and 8 terms in the effective Lagrangian

Going beyond dimension 6

Reason for dimension 8 operators like

$$\begin{aligned}
\mathcal{L}_{S,0} &= \left[(D_\mu\Phi)^\dagger D_\nu\Phi\right] \times \left[(D^\mu\Phi)^\dagger D^\nu\Phi\right] \\
\mathcal{L}_{M,1} &= \mathrm{Tr}\left[\hat{W}_{\mu\nu}\hat{W}^{\nu\beta}\right] \times \left[(D_\beta\Phi)^\dagger D^\mu\Phi\right] \\
\mathcal{L}_{T,1} &= \mathrm{Tr}\left[\hat{W}_{\alpha\nu}\hat{W}^{\mu\beta}\right] \times \mathrm{Tr}\left[\hat{W}_{\mu\beta}\hat{W}^{\alpha\nu}\right]
\end{aligned}$$

- Dimension 6 operators only do not allow to parameterize $VVVV$ vertex with arbitrary helicities of the four gauge bosons

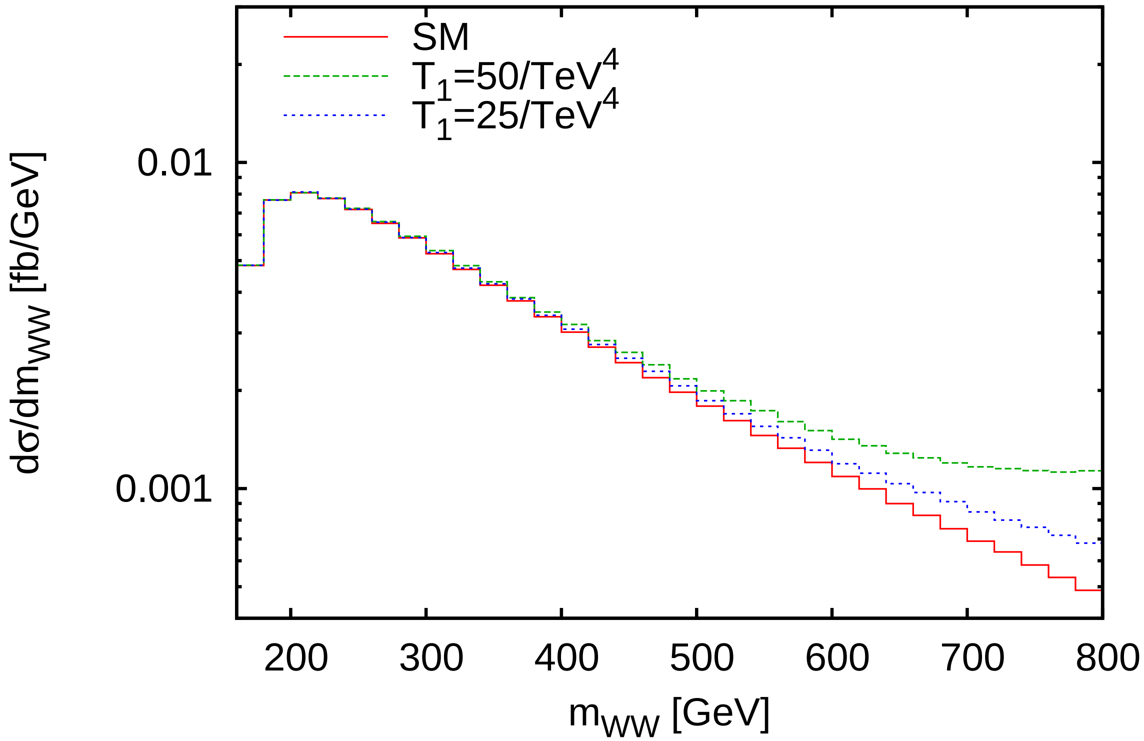
For example: $\mathcal{L}_{S,0}$ is needed to describe $V_L V_L \to V_L V_L$ scattering

- New physics may appear at 1-loop level for dimension 6 operators but at tree level for some dimension 8 operators

$VV \to W^+W^-$ with dimension 8 operators

Effect of $\mathcal{L}_{eff} = \frac{f_{M,1}}{\Lambda^4} \mathrm{Tr}\left[\hat{W}_{\alpha\nu}\hat{W}^{\mu\beta}\right] \times \mathrm{Tr}\left[\hat{W}_{\mu\beta}\hat{W}^{\alpha\nu}\right]$

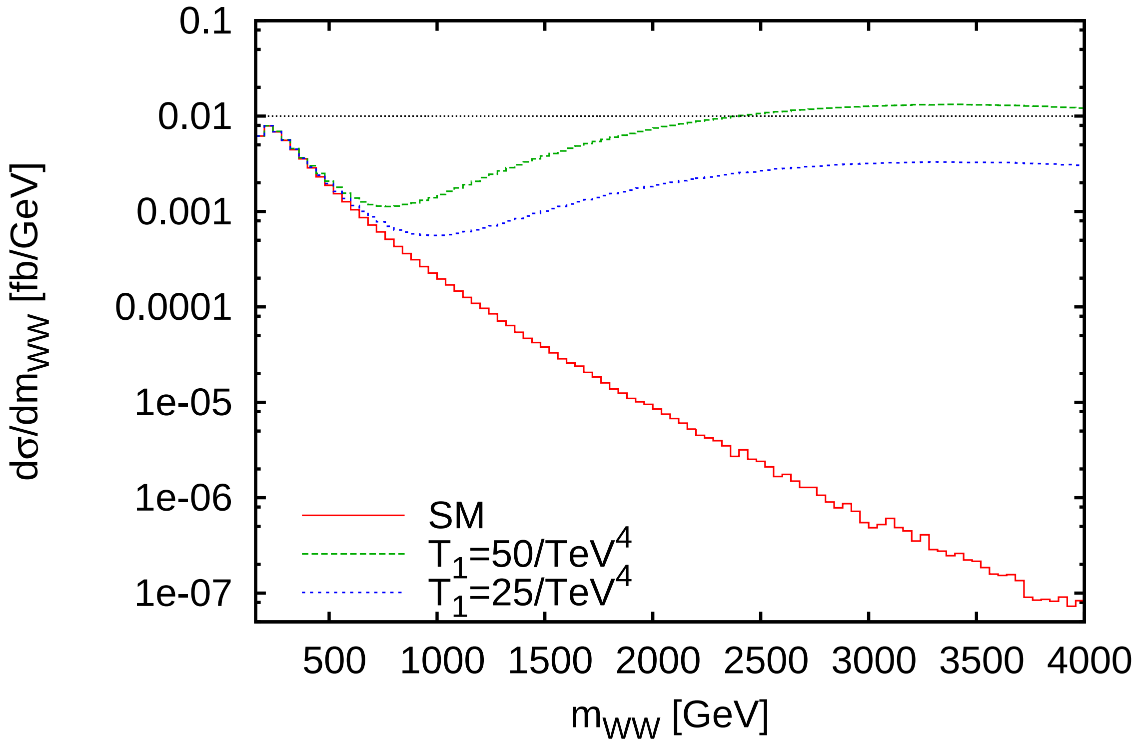
with $T_1 = \frac{f_{M,1}}{\Lambda^4}$ constant on $pp \to W^+W^- jj \to e^+\nu_e\mu^-\bar{\nu}_\mu jj$



- Small increase in cross section at high WW invariant mass??

$VV \rightarrow W^+W^-$ with dimension 8 operators

Effect of constant $T_1 = \frac{f_{M,1}}{\Lambda^4}$ on $pp \rightarrow W^+W^- jj \rightarrow e^+\nu_e\mu^-\bar{\nu}_\mu jj$



- Huge increase in cross section at high m_{WW} is completely unphysical
- Need form factor for analysis or some other unitarization procedure

Conclusions

- VBF production of a light Higgs provides for important input to the coupling measurements
- VBS at high VV invariant mass and high p_T of the weak bosons complements these measurements
- Model independent parameterizations of deviations from the SM are provided by a variety of programs
- Form factors or some other unitarization procedure cannot be avoided when using effective Lagrangians for VV scattering at the LHC (for quite some time)