W^+W^-H production through bottom quarks fusion at hadron colliders

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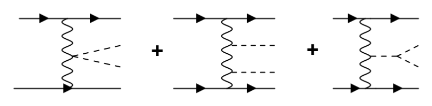
Overview

Motivation : $b\,\bar{b} \longrightarrow W^+W^-H$

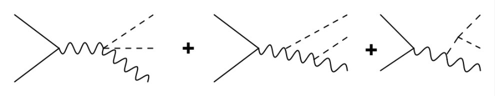
- Higgs sector in SM is not well explored, in particular HHH, $HHHH$ and $VVHH$ couplings are still not well measured.
- Few processes can probe the $VVHH$ coupling.
  - VBF mechanism for HH production



At HL-LHC the bound could be $0.55 < \kappa_{V_2H_2} < 1.65$ at 95% confidence level. But the bound comes from both coupling $WWHH$ and $ZZHH$.

Motivation

- Higgs-strahlung : HHV (V=W, Z) production



At the HL-LHC the bound will be quite weak
$-9 < \kappa_{V_2H_2} < 11$.

- VVH (V=W, Z) production

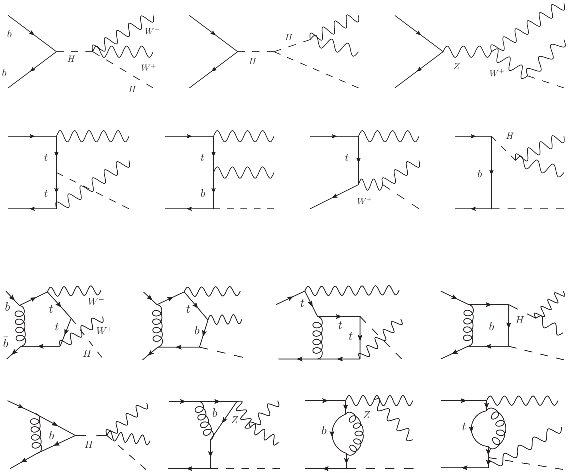
We can probe two *VVHH* couplings separately.

Motivation

$pp \to WWH(\text{LO})$	gg	$q\bar{q}$	$b\bar{b}$
$\sigma(fb)$ at 14TeV	0.29	8.66	0.25
$\sigma(fb)$ at 27TeV	1.34	23.0	1.31
$\sigma(fb)$ at 100TeV	17.4	126.8	20.6

- The $b\bar{b}$ contribution is sizeable. One should probe it in QCD regime.
- One can study the polarization dependence of physical observables which will be very useful for background suppression.

Feynman diagrams :

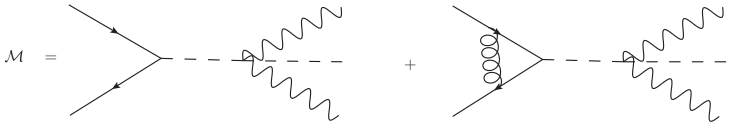


Feynman Diagrams :

- Total number of diagrams :
  - LO : 20 diagrams
  - NLO : Pentagon + Box + Triangle + Self Energy diagrams. Total 121 NLO diagrams.

- The trick is to calculate the minimum no. of diagrams, called *prototype diagrams* and then map the rest of the diagrams to those prototype diagrams.
  - LO prototype diagrams are 10
  - Loop-level prototype diagrams are 30.

Coupling Order :



$$\mathcal{M} \sim g_w^3 \mathcal{M}_{LO} + g_s^2 g_w^3 \mathcal{M}_{NLO} + \mathcal{O}(g_s^4)$$

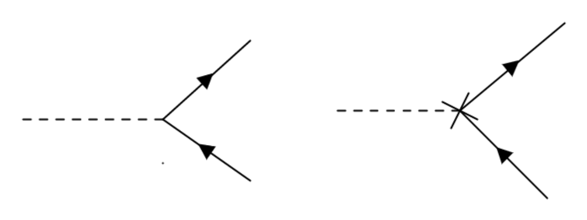
$$|\mathcal{M}|^2 \sim \alpha_w^3 |\mathcal{M}_{LO}|^2 + \alpha_s \alpha_w^3 . 2Re(\mathcal{M}_{LO} . \mathcal{M}_{NLO}^*) + \mathcal{O}(\alpha_s^2)$$

Techniques to compute amplitudes :

- We compute helicity amplitudes by using spinor helicity formalism at the matrix element level.
- We use four-dimensional helicity (FDH) scheme to compute the amplitudes where all the γ-matrices, momentums and spinors are taken in 4-dimensions.
- In one-loop amplitude, individual one-loop Feynman diagram will give rise to tensor integrals containing powers of the loop momentum in the numerator.
- We use an in-house routine *OVReduce*, based on Oldenborgh-Vermaseren reduction techniques to reduce tensor integrals in terms of scalar integrals.
- We use the 'OneLOop' package for scalar integrals computation.

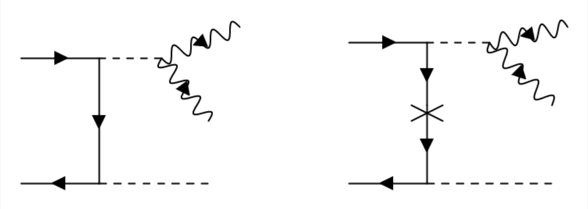
UV divergence : Vertex CT diagrams

- QCD renormalizes the fermion mass.
- Higgs vertex will be renormalized due to mass involved in coupling.



- The Coupling strength of $Hf\bar{f}$ vertex is $-\frac{ig}{2}\frac{m_f}{m_W}$.
- Counterterm for $Hf\bar{f}$ vertex is $-\frac{ig}{2}\frac{\delta m_f}{m_W}$. Where $\delta m_f = -\frac{\alpha_s}{4\pi}C_F\frac{6}{\epsilon}$.

UV divergence : Self-energy CT diagrams

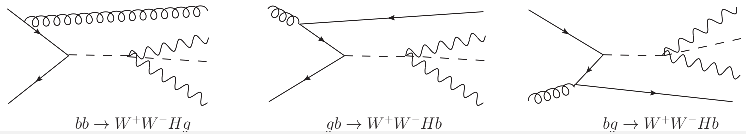


- Counterterm for self energy diagram : $-i(\not{p}\delta Z_2 - m_f \delta Z_m)$
- $\delta Z_2 = -\frac{\alpha_s}{4\pi} C_F \frac{2}{\epsilon}$ and $\delta Z_m = -\frac{\alpha_s}{4\pi} C_F \frac{8}{\epsilon}$.

Infrared divergence :

- IR or "mass singularities" arises from two kinds of singularities called the *collinear* and *soft* singularity. Singularities appear as $\sim ln(m/Q)$. where m is the mass of the particle and Q is a large scale.
  For the massless case
  $$\sim 1/\epsilon\,,\ 1/\epsilon^2 \qquad [\,\epsilon = (4-D)/2]$$
- Because of light quarks and gauge bosons, most of the one-loop diagrams are IR singular.
- The real emission diagrams are also IR singular in soft and collinear regimes.
- The real emission and renormalized virtual amplitudes are both divergent in 4-dimension, but the sum of these two is finite.
- Three real emission sub-process can contribute to σ^{NLO}.
  1. $b\bar{b} \to W^+W^-Hg$, 2. $g\bar{b} \to W^+W^-H\bar{b}$ and 3. $bg \to W^+W^-Hb$

Subtraction scheme



- The real emission sub-processes starting with gluon have t-quark resonant diagrams which jeopardize the perturbative computations.
- We use b-quark tagging with 100% efficiency. We exclude these two sub-processes to avoid the t-quark resonances.
- We implemented the Catani-Saymour dipole subtraction method to remove IR singularities. The I-term exactly cancel the IR singularities in virtual diagrams and dipole terms $\mathcal{D}_{ij,k}$ exactly cancel IR singularities in real emission diagrams.

Results : SM predictions

We took SM parameters from PDG 2016. We use CT14lo and CT14nlo PDF set for LO and NLO cross section calculation respectively. We take $\overline{MS}$ and On-shell renormalization scheme for massless and massive fermions respectively. The following results are in the ab unit for different CMEs with the scale uncertainties.

TeV	$\sigma_0(\alpha_w^3)$	$\sigma_{qcd}^{NLO}(\alpha_s\alpha_w^3)$	RE
14	$217^{+16.1\%}_{-18.9\%}$	$289^{+17.6\%}_{-20.8}$	33.2%
27	$1086^{+19.2\%}_{-20.5}$	$1559^{+18.0\%}_{-20.8}$	43.6%
100	$15258^{+22.0\%}_{-20.9\%}$	$23097^{+20.6\%}_{-21.0\%}$	51.4%

The relative enhancement is defined as $RE = (\frac{\sigma_{qcd}^{NLO} - \sigma_0}{\sigma_0})$. We choose a dynamical scale as

$$\mu_R = \mu_F = \mu_0 = \frac{1}{3}\left(\sqrt{p_{T,W^+}^2 + M_W^2} + \sqrt{p_{T,W^-}^2 + M_W^2} + \sqrt{p_{T,H}^2 + M_H^2}\right)$$

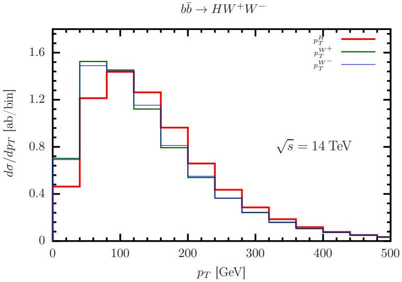
Results : SM predictions

Polarization dependence of cross section :

Pol.(W^+W^-)	14 TeV (ab)			100 TeV (ab)		
	σ_0	σ_{qcd}^{NLO}	$RE(\%)$	σ_0	σ_{qcd}^{NLO}	$RE(\%)$
$++$	13	18	38.5	702	1056	50.4
$+-$	18	25	38.9	965	1499	55.3
$+0$	37	49	32.4	2568	3336	29.9
$-+$	4	6	50.0	229	334	45.9
$--$	13	18	38.5	707	1044	47.7
-0	22	28	27.3	1454	1346	-7.4
$0+$	22	28	27.3	1470	1216	-17.3
$0-$	37	49	32.4	2583	3151	22.0
00	51	67	31.4	4490	9748	117.1
$\sum$	217	289	32.2	15258	23097	51.4

Where $+ \equiv \frac{1}{\sqrt{2}}(\epsilon_x + i\epsilon_y)$, $- \equiv \frac{1}{\sqrt{2}}(\epsilon_x - i\epsilon_y)$ and $0 \equiv \epsilon_z$.
Here we can see that there are huge contributions and increments in '00' polarization mode.

p_T-distributions :



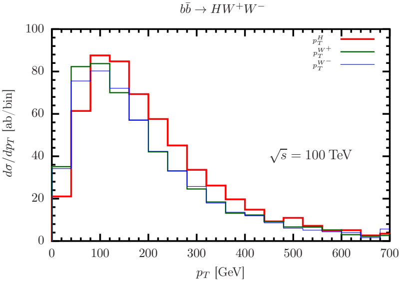


Figure: The NLO differential cross section distribution with respect to transverse momentums (p_T) for 14 and 100 TeV CMEs.

Invariant Mass distributions :

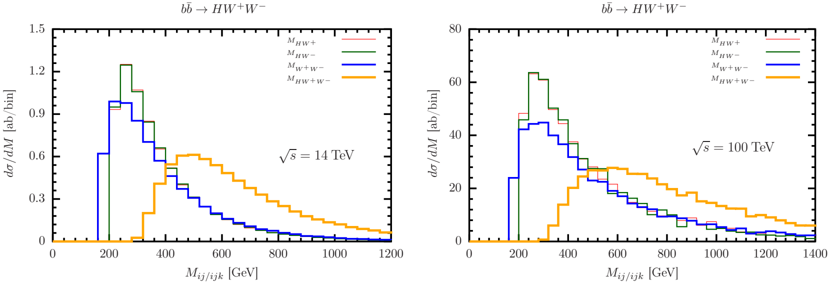


Figure: The NLO differential cross section distribution with respect to invariant masses ($M_{ij/ijk}$) for 14 and 100 TeV CMEs.

Differential distributions :

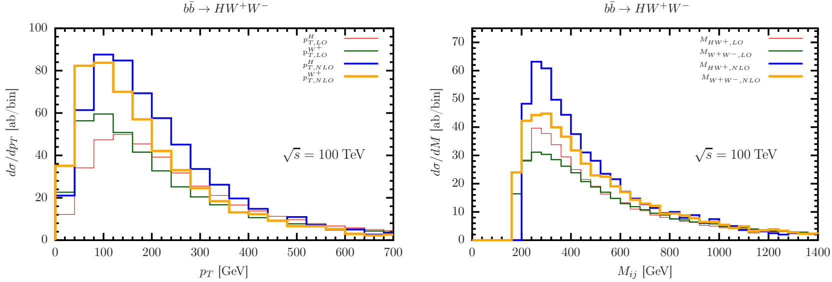


Figure: The LO and NLO differential cross section distribution with respect to transverse momentums (p_T) and invariant masses ($M_{ij/ijk}$) for 100 TeV CME.

Differential distributions :

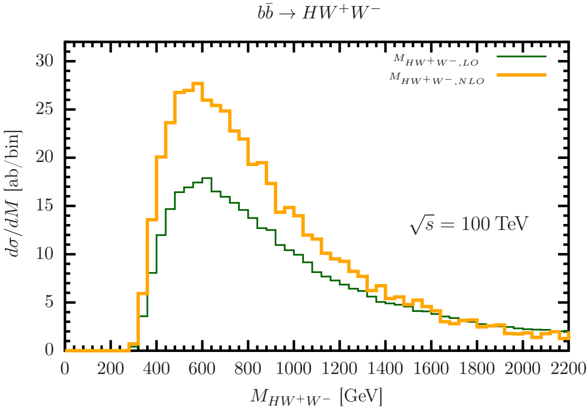


Figure: The LO and NLO differential cross section distribution with respect to invariant masses (M_{WWH}) for 100 TeV CME.

Anomalous coupling effects : κ-framework

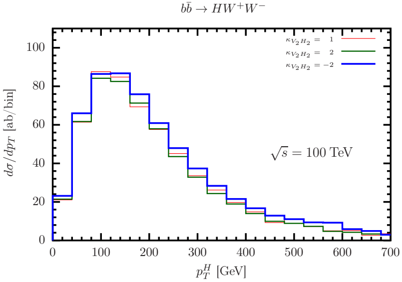
CME(TeV)	$\kappa_{V_2H_2}$	σ^{LO}[ab]	RI	σ^{NLO}[ab]	RI
14	1.0 (SM)	217		289	
	2.0	216	[-0.5%]	288	[-0.3%]
	-2.0	222	[$+2.3\%$]	295	[$+2.1\%$]
100	1.0(SM)	15258		23097	
	2.0	14925	[-2.2%]	22607	[-2.1%]
	-2.0	16997	[$+11.4\%$]	25465	[$+10.3\%$]

Table: Effect of anomalous *WWHH* coupling on the total cross section at 14 and 100 TeV CMEs. Where RI $= \frac{\sigma_{\kappa_{V_2H_2}} - \sigma_{SM}}{\sigma_{SM}}$.

$\kappa_{V_2H_2}$	σ^{LO}[ab]	RI	σ^{NLO}[ab]	RI
1.0 (SM)	4490		9748	
2.0	4159	[-7.4%]	9544	[-2.1%]
-2.0	6164	[$+37.2\%$]	11993	[$+23.0\%$]

Table: Effect of anomalous *VVHH* coupling in ‘00’ mode at 100 TeV CME.

Differential distributions :



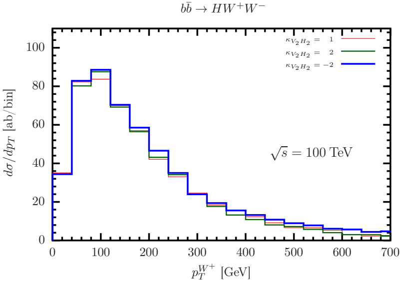


Figure: Effect of anomalous *VVHH* coupling on the differential cross section distribution at 100 TeV CME.

Differential distributions :

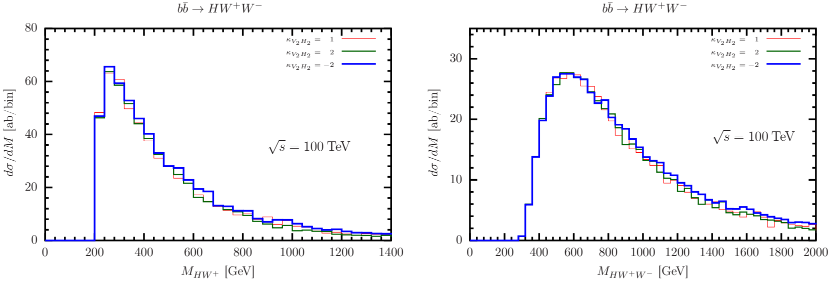


Figure: Effect of anomalous *VVHH* coupling on the differential cross section distribution at 100 TeV CME.

Summary

- We have focused on the NLO QCD correction to $b\bar{b} \to W^+W^-H$. This process has significant dependence on $VVHH$ coupling.
- The contribution of this process to $pp \to W^+W^-H$ is only about $10 - 15\%$ of that light quark scattering. But when both W-bosons are longitudinally polarized then this fraction can increase to 50%.
- At 100 TeV the NLO corrections are about 50% but the corrections are about 115%, when both W-bosons are longitudinally polarized.
- Our study suggests that the measurement of the polarization of the final state W/Z-bosons can be a useful tool to measure the couplings of the vector bosons and Higgs boson.
- Total cross section enhanced by 10% and cross section in '00' mode enhanced by $20 - 30\%$ when we set $\kappa_{V_2H_2} = -2$.
- We find that the invariant mass and the p_T distributions are considerably harder for the negative values of $\kappa_{V_2H_2}$. This can also be useful to put a stronger bound on the coupling.

Thank You