Sensitivity to measure the anomalous gauge couplings of the Higgs boson via W^+W^+ scattering at the LHC*

Zhen Zhang,† Guo-Ming Chen, Min Yang, Bei-Jiang Liu, Jun-Quan Tao, Zhi-Cheng Tang, Xiang-Wei Meng, Jia-Guo Bian, Zheng Wang, Jian Wang, Yu-Sheng Lu, Zhu-Hao Li, and Jing-Jing Zang
Institute of High Energy Physics Chinese Academy of Sciences, Beijing 100049, China

Bin Zhang
Department of Physics, Tsinghua University, Beijing 100080, China

A sensitive way to test the anomalous HVV ($V = W^{\pm}, Z^0$) couplings via $pp \to W^+W^+\ jj \to \ell^+\nu\ell^+\nu jj$ at LHC was proposed by Bin Zhang, Yu-Ping Kuang, Hong-Jian He and C.-P. Yuan in Ref. [1]. We studied the sensitivity to measure the anomalous gauge couplings of Higgs boson with optimized cuts. In this way, the sensitivity can be enhanced. Based on the optimized cuts and distribution of $\Delta Pt(\ell\ell)$, the measurement of the couplings can be further improved via maximum likelihood fit. It shows that, with an integrated luminosity of $300 fb^{-1}$, the anomalous HWW and HZZ couplings can be measured at the level of 0.007 - 0.032 TeV^{-1} and 0.007 - 0.013 TeV^{-1}, respectively, for the linearly realized effective Lagrangian.

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I. INTRODUCTION

The standard mode (SM) of the electroweak interactions has proven to be very successful in explaining all available experimental data at the scale $\lesssim \mathcal{O}$ (100)GeV. However, the mechanism of electroweak symmetry breaking (EWSB) is still one of the most profound puzzles in particle physics. If a light Higgs boson candidate H is found in the future collider experiments, the next important task is to experimentally measure the gauge interactions of this Higgs scalar and explore the nature of the electroweak symmetry breaking mechanism (EWSBM). The detection of the anomalous HVV couplings (AHVVC) will point to new physics beyond the SM underlying the EWSBM. Also, testing the effective anomalous gauge couplings of the Higgs boson can discriminate the EWSB sector of the new physics model from that of the SM.

The anomalous HVV couplings of the Higgs boson can arise from the dimension-3 effective operator in a nonlinearly realized Higgs sector or from the dimension-6 effective operators in a linearly realized Higgs sector [1]. Compared to them, that rising from the latter one is more sensitive [1, 2]. So the following study of AHVVC concentrates on the sector of linearly realized effective Lagrangians. In a linearly realized Higgs sector, the C and P conserving effective Lagrangian up to dimension-6 operators containing a Higgs doublet Φ and the weak bosons V^a is given by

$$L_{eff} = \sum_n \frac{f_n}{\Lambda^2}\mathcal{O}_n, \tag{1}$$

where $\mathcal{O}_n$'s are dim-6 operators composed of Φ and the EW gauge field (cf. Ref. [3]), f_n's are the anomalous coupling constants. The anomalous coupling constants are related to the following AHVVC in terms of H, $W^{\pm}$, Z, γ [3]:

$$\begin{aligned} L^H_{eff} &= \mathrm{g}H\gamma\gamma H A_{\mu\nu}A^{\mu\nu} + \mathrm{g}^{(1)}_{HZ\gamma}A_{\mu\nu}Z^{\mu}\partial^{\nu}H \\ &+\mathrm{g}^{(2)}_{HZ\gamma}HA_{\mu\nu}Z^{\mu\nu} + \mathrm{g}^{(1)}_{HZZ}Z_{\mu\nu}Z^{\mu}\partial^{\nu}H \\ &+\mathrm{g}^{(2)}_{HZZ}HZ_{\mu\nu}Z^{\mu\nu} + \mathrm{g}^{(2)}_{HWW}HW^{+}_{\mu\nu}W^{-\mu\nu} \\ &+\mathrm{g}^{(1)}_{HWW}(W^{+}_{\mu\nu}W^{-\mu}\partial^{\nu}H + h.c.), \end{aligned} \tag{2}$$

where

$$\begin{aligned} \mathrm{g}_{H\gamma\gamma} &= -(\frac{gm_W}{\Lambda^2})\frac{s^2(f_{BB}+f_{WW})}{2}, \\ \mathrm{g}^{(1)}_{HZ\gamma} &= (\frac{gm_W}{\Lambda^2})\frac{s(f_W-f_B)}{2c}, \\ \mathrm{g}^{(2)}_{HZ\gamma} &= (\frac{gm_W}{\Lambda^2})\frac{s(s^2f_{BB}-c^2f_{WW})}{c}, \\ \mathrm{g}^{(1)}_{HZZ} &= (\frac{gm_W}{\Lambda^2})\frac{c^2f_W+s^2f_B}{2c^2}, \\ \mathrm{g}^{(2)}_{HZZ} &= -(\frac{gm_W}{\Lambda^2})\frac{s^4f_{BB}+c^4f_{WW}}{2c^2}, \\ \mathrm{g}^{(1)}_{HWW} &= (\frac{gm_W}{\Lambda^2})\frac{f_W}{2}, \\ \mathrm{g}^{(2)}_{HWW} &= -(\frac{gm_W}{\Lambda^2})f_{WW}, \end{aligned} \tag{3}$$

with s$\equiv \sin\theta_W$,c$\equiv \cos\theta_W$. Detailed calculations show that the contributions of f_B and f_{BB} to the $pp \to W^+W^+jj \to \ell^+\nu\ell^+\nu jj$ channel are small even if they are of the same order of magnitude as the anomalous coupling constants f_{WW} and f_W [1]. Hence, we shall ignore their contributions in the following analysis, and discuss only the sensitivity to the measurement of f_{WW}

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†Electronic address: `zzhang@mail.ihep.ac.cn`

and f_W separately, i.e., assuming only one of the anomalous coupling constants is dominant at a time as done in Ref. [1].

In order to improve the measurement of f_{WW} and f_W, the applied cuts [4] in Ref. [1] are optimized and the method of a maximum likelihood fit is used to extract these constants. In addition to the jet cuts and leptonic cuts [4], we find the $Pt(\nu\nu)$, i.e., $\sqrt{[P_x(\nu1) + P_x(\nu2)]^2 + [P_y(\nu1) + P_y(\nu2)]^2}$, is an effective cut to suppress backgrounds, so the cut is also applied. After optimizing cuts, the $\Delta Pt(\ell\ell)$ distribution is still sensitive to the values of anomalous gauge coupling constants, so it is used to further enhance the measurement of the AHVVC constants by maximum likelihood fit.

II. EVENT SELECTION

The matrix element generator of the $pp \to W^+W^+jj \to \ell^+\nu\ell^+\nu jj$ is developed based on Ref. [1], and the parton shower is done with PYTHIA [5]. So the events of the channel can be produced. In this channel, the signal is defined as $N_S = N_{NonSM} - N_{SM}$, where N_{NonSM} is the number of events correponding to the values of anomalous coupling constants are not zero and N_{SM} is the number of SM events correponding to the values of anomalous couplings constant are zero. The SM events are considered to be intrinsic electroweak background as in Ref. [1].

In order to avoid large hadronic backgrounds at the LHC, the "gold-plated"pure leptonic decay modes of the final state W are chosen. Even in this case, there are still other backgrounds to be eliminated [6–9]. The main backgrounds are listed in Table I.

Some of the backgrounds are copious at the LHC and Monte Carlo samples that correspond to 300 fb^{-1} are much too large to be fully produced by computer. Selections at generator-level have been applied in order to be able to select high transverse momentum leptons and tag jet events, and reject events that have negligible chance of producing background to the signal.

The generator-level pre-selection of events that contribute to the signal is straightforward. Cuts are applied on the transverse momentum of positive charged leptons, on their pseudorapidity, on the invariant mass of the two leptons and on $\cos\phi(\ell\ell)$. In addition, transverse momentus and direction of jet are applied on the events produced with ALPGEN [10]. All the cuts are listed in Table II. With pre-selection, there are enough background events produced for the integrated luminosity of $300fb^{-1}$ as shown in Table I.

In order to suppress these backgrounds, the following cuts [4] are suggested by J. Bager:

Leptonic cuts	Jet cuts
$\mid y(\ell) \mid < 2.0,$	
$p_T(\ell) > 70GeV,$	$3.0 < \|y(j_{tag})\| < 5.0,$
$\Delta pt(\ell\ell) > 200GeV,$	$p_T(j_{tag}) > 40GeV,$
$\cos\phi(\ell\ell) < -0.8,$	$p_T(j_{veto}) > 60GeV,$
$M(\ell\ell) > 250GeV,$	$\|y(j_{veto})\| < 3.0,$

where the forward tag jet corresponds to the j in $pp \to W^+W^+jj \to \ell^+\nu\ell^+\nu jj$ and the requirement of vetoing the central jet can be used to suppress top quark background.

In addition, we also ask the events have not a minus charged lepton whose transverse momentum is larger than 5 GeV. Even with all the above cuts, the intrinsic electroweak backgrounds are still much more than signal when the values of anomalous gauge couplings constants are not very large. So we produced an intrinsic electroweak background sample and two samples corresponding the values of f_{WW}/Λ^2 are 1.6 TeV^{-2} and 3.0 TeV^{-2} separately to study them. Each of the three samples corresponds to 10000 events. Through studying them, we find that a cut applied on $Pt(\nu\nu)$ can effectively suppress the intrinsic electroweak background. In addition, the $Pt(\nu\nu)$ corresponds to missing transverse energy (MET), i.e., $E_T^{miss} = \sqrt{(E_x^{miss})^2 + (E_y^{miss})^2}$, which can be measured in experiment. The distributions of $Pt(\nu\nu)$ are shown in Fig. 1(a). With the MET cut being used, some leptonic cuts listed in Ref. [4] are slightly adjusted in order to get a larger $S/\sqrt{S+B}$. The cut applied on pseudorapidity of lepton is released and the cut applied on the transverse momentum of leptons is tightened. The optimized cuts can be found in Table III.

With the optimized cuts, the remaining background events are listed in Table IV with an integrated luminosity of 300fb $^{-1}$. For the $W^{\pm}Z$+njets channel, we assume the tag cut, veto cut and MET cut are independent to approximately estimate the cross section after no events left using leptonic cuts. Because the *g exhange* channel is a subprocess of $W^+W^+ \to W^+W^+$ in PYTHIA and it is not easy to only produce the events of the subprocess, we use the cross sections listed in Ref. [6, 7] to estimate the events for *g exhange* channel with different cuts except MET cut. But the MET efficience of $W^+W^+ \to W^+W^+$ instead of MET efficience of *g exhange* channel was used to estimate cross section of *g exhange* channel in Table IV.

III. EVENT COUNTING EXPERIMENT

The AHVVC constants can be measured through event counting. With optimized cuts, the number of events with an integrated luminosity of $300fb^{-1}$, for various values of m_H and f_{WW}/Λ^2, can be obtained as shown in Table V when f_{WW} dominates. Compared to the Table IX-B in Ref. [1], the number of intrinsic electroweak backgrounds decreases by one third, but the number of signal events slightly increases. Since the event number is rather small for the case of $f_{WW} = 0$, the Poisson statistics was used for setting the exclusion limit which is only based on the N_B. We find that $N_B = 9$ in Table V, so

TABLE I: Main backgrounds and produced events after pre-selections at generator level.

channels	generator	produced events	integrated luminosity
$W^{\pm}Z$+njets (n=1,2,3)	ALPGEN	138000	$300fb^{-1}$
ZZ+njets (n=1,2,3)	ALPGEN	94000	$660fb^{-1}$
$t\bar{t}$	PYTHIA	50300	$310fb^{-1}$
$t\bar{t}\ Z^0$	ALPGEN	1000	$590fb^{-1}$
$t\bar{t}\ W^+$	ALPGEN	1000	$330fb^{-1}$

TABLE II: The cuts used for pre-selection.

channels	Leptonic cuts	Jet cuts	MET cut
$W^{\pm}Z$+njets (n=1,2,3)	$\mid y(\ell^+) \mid < 2.4$	$p_T(j) > 30GeV$, $3.0 < \lvert y(j_{tag}) \rvert < 5.0$	$MET > 25GeV$
ZZ+njets (n=1,2,3)	$\mid y(\ell^+) \mid < 2.4$, $p_T(\ell^+) > 5GeV$	$3.0 < \lvert y(j_{tag}) \rvert < 5.0$	
$t\bar{t}$	$\mid y(\ell^+) \mid < 2.4$, $p_T(\ell^+) > 40GeV$, $M(\ell^+\ell^+) > 40GeV$, $\cos\phi(\ell^+\ell^+) < -0.5$		
$t\bar{t}\ Z^0$	$\mid y(\ell^+) \mid < 2.4$, $p_T(\ell^+) > 5GeV$		
$t\bar{t}\ W^+$	$\mid y(\ell^+) \mid < 2.4$, $p_T(\ell^+) > 5GeV$		

TABLE III: The optimized cuts for the process $pp \to W^+W^+jj \to \ell^+\nu\ell^+\nu jj$.

Leptonic cuts	Jet cuts	MET cut
$\mid y(\ell^+) \mid < 2.4$		
$p_T(\ell^+) > 80GeV$	$3.0 < \lvert y(j_{tag}) \rvert < 5.0$	
$\Delta pt(\ell^+\ell^+) > 250GeV$	$p_T(j_{tag}) > 40GeV$	$MET > 50GeV$
$\cos\phi(\ell^+\ell^+) < -0.8$	$p_T(j_{veto}) > 60GeV$	
$M(\ell^+\ell^+) > 200GeV$	$\lvert y(j_{veto}) \rvert < 3.0$	
$p_T(\ell^-_{veto}) > 5GeV$		

the 95% C.L. bounds on f_{WW}/Λ^2 can be determined in Eq. (4).

$$-1.5 < f_{WW}/\Lambda^2 < 1.3, \tag{4}$$

for 115GeV $\lesssim m_H \lesssim$ 300GeV.

In the case that f_W dominates, the results are listed in Table VI. If no anomalous coupling effect is found via the process, the corresponding 95% C.L. bounds on f_W/Λ^2 (inunits of TeV^{-2}) can also be set:

$$-1.0 < f_W/\Lambda^2 < 0.9, \tag{5}$$

for 115GeV $\lesssim m_H \lesssim$ 300GeV.

From the Eqs. (3), (4), (5), we can obtain the 95% C.L. bounds on g^i_{HVV}, i= 1, 2 (in units of TeV^{-2}) as shown in Eq. (6).

$$\begin{aligned}
-0.026 &< g^{(1)}_{HWW} < 0.023,\\
-0.026 &< g^{(1)}_{HZZ} < 0.023,\\
-0.014 &< g^{(1)}_{HZ\gamma} < 0.013,\\
-0.067 &< g^{(2)}_{HWW} < 0.078,\\
-0.026 &< g^{(2)}_{HZZ} < 0.030,\\
-0.015 &< g^{(2)}_{HZ\gamma} < 0.017.
\end{aligned} \tag{6}$$

IV. EXTRACTION OF ANOMALOUS GAUGE COUPLINGS CONSTANTS VIA MAXIMUM LIKELIHOOD FIT

The total number of events and normalized $\Delta Pt(\ell\ell)$ are functions of the value of the anomalous gauge coupling constants for a given mass of Higgs boson, so the values of the constants can be extracted with the two pieces of information. As done in Sec. III, we will discuss the sensitivity of the $W^+\ W^+$ scattering to the measurement of f_{WW} and f_W separately, and ignore the contribution of f_B and f_{BB}. We assume the mass of Higgs is 115 GeV. Because the sign of f_W and f_{WW} can not be discriminated by theory and experiment and the distribution of the total number of events is asymmetric for all of the f_W and f_{WW} range, we will consider their plus and minus sides separately.

In the case that f_{WW} dominates and $f_{WW} \geq 0$, the distribution of the total number of events as a function of f_{WW} in Fig. 2(a) can be described by

$$N_{tot}(f_{WW}/\Lambda^2) = 4.9 \times f_{WW}/\Lambda^2 + 8.4. \tag{7}$$

The normalized distribution of $\Delta Pt(\ell\ell)$ is very sensitive to the value of f_{WW}/Λ^2 as shown in Fig. 1(b). In order

TABLE IV: Number of events at the LHC, with an integrated luminosity of 300fb $^{-1}$, for $pp \to W^+W^+jj \to \ell^+\nu\ell^+\nu jj$ ($\ell^+ = e^+$ or μ^+).

channels	Leptonic cuts only/eff.	+tag only/tag eff.	+ tag +Veto/Veto eff.	+Veto + tag +MET/MET eff.
$W^{\pm}Z$+njets (n=1,2,3)	$97/7 \times 10^{-4}$	< 1 /1%	<0.15 /15%	<0.12 /75%
ZZ +njets (n=1,2,3)	$10/2 \times 10^{-4}$	0.5 /5%	0.4 /85%	0.02 /5%
$t\bar{t}$	$151/3 \times 10^{-3}$	1 /7$\times10^{-3}$	< 0.075 /7.5%	<0.06 /85%
$t\bar{t}\ Z^0$	$< 1/ < 10^{-3}$	< 0.01 /<1%	<0.001 /<10%	<0.001 /<100%
$t\bar{t}\ W^+$	$< 1/ < 10^{-3}$	< 0.01 /<1%	<0.001 /<10%	<0.001 /<100%
g exhange	45	3.5 /7.7%	0.2 /6%	0.13 /66%

TABLE V: Number of events at the LHC, with an integrated luminosity of 300fb^{-1}, for $pp \to W^+W^+jj \to \ell^+\nu\ell^+\nu jj$ ($\ell^+ = e^+$ or μ^+) in the linearly realized effective Lagrangian with various values of m_H and f_{WW}/Λ^2.

$m_H(GeV)$	$f_{WW}/\Lambda^2(\mathrm{TeV}^{-2})$								
	-4.0	-3.0	-1.9	-1.5	0.0	1.3	1.9	3.0	4.0
115	40	26	18	14	9	14	18	28	42
130	41	26	18	14	9	14	18	29	42
200	42	27	18	14	9	14	18	29	43
300	44	27	19	15	9	15	19	30	45

to extract the value of f_{WW}/Λ^2 with the piece of information, we divide the total range of $\Delta Pt(\ell\ell)$ into tree bins, i.e., 0 GeV - 600 GeV, 600 GeV - 1000 GeV and 1000 GeV - ∞. The percentage of events as a function of the values of f_{WW}/Λ^2 can be got from produced large samples in each bin. Figures 2(b) (c) (d) show these percentages which are described by P(i,f_{WW}) in Eqs. (8) for three bins respectively,

$$\begin{aligned} P(1, f_{WW}/\Lambda^2) &= -0.099 \times f_{WW}/\Lambda^2 + 0.901, \\ P(2, f_{WW}/\Lambda^2) &= 0.055 \times f_{WW}/\Lambda^2 + 0.088, \\ P(3, f_{WW}/\Lambda^2) &= 0.040 \times f_{WW}/\Lambda^2 + 0.014, \end{aligned} \tag{8}$$

where $i = 1, 2, 3$, respect to 3 bins.

Then, the expected number of events in each bin is expressed as:

$$N_i^{exp}(f_{WW}/\Lambda^2) = N_{tot}(f_{WW}/\Lambda^2) \times P(i, f_{WW}/\Lambda^2). \tag{9}$$

Finally, the log maximum likelihood function is written as:

$$\begin{aligned} \ln L &= \ln \prod_{i=1}^{n} P(N_i^{obs}, N_i^{exp}) \\ &= \sum_{i=1}^{n} \ln \frac{(N_i^{exp})^{N_i^{obs}}}{N_i^{obs}!} e^{N_i^{exp}}, \end{aligned} \tag{10}$$

where N_i^{obs} is the observed number of events in the ith bin, where $i = 1, 2, 3$. The value of f_{WW}/Λ^2 can be extracted by minimizing the -ln L with Minuit in ROOT [11].

There are 1000 SM MC samples, each corresponding to an integrated luminosity of 300 fb^{-1}, used to perform the fit. The extracted values of f_{WW}/Λ^2 will be shown in Fig. 3(a) which can be well-fitted by a Gaussian function.

Similarly, when $f_{WW} \leq 0$, the values of f_{WW}/Λ^2 can be obtained in the same way as shown in Fig. 3(b). The bounds on f_{WW} are:

$$1\sigma : -0.62 < f_{WW}/\Lambda^2 < 0.58. \tag{11}$$

In the case that f_W dominates, with the same method, the extracted values of f_W/Λ^2 are shown in Fig. 4. The bounds on f_W/Λ^2 are:

$$1\sigma : -0.27 < f_W/\Lambda^2 < 0.33. \tag{12}$$

Based on Eqs. (3), (9), (10), we obtain the corresponding bounds on g^i_{HVV}, i= 1, 2 (in units of TeV^{-1}):

$$\begin{aligned} 1\sigma : -0.007 &< g^{(1)}_{HWW} < 0.008, \\ -0.007 &< g^{(1)}_{HZZ} < 0.008, \\ -0.004 &< g^{(1)}_{HZ\gamma} < 0.005, \\ -0.030 &< g^{(2)}_{HWW} < 0.032, \\ -0.011 &< g^{(2)}_{HZZ} < 0.013, \\ -0.007 &< g^{(2)}_{HZ\gamma} < 0.006. \end{aligned} \tag{13}$$

From the above constraints on $g^{(i)}_{HVV}$, i=1, 2, we can see that the bounds on $g^{(i)}_{HVV}$ are at the level of O (10^{-3} - 10^{-2}) TeV^{-1}. The constraints on $g^{(i)}_{HWW}$ are tighter than that obtained via event counting. Compared to Ref. [1], the predicted precision of the measurements increases by a factor of two. According to Ref. [12], the anomalous HZZ coupling constants $g^{(1)}_{HZZ}$ and $g^{(2)}_{HZZ}$ can be tested rather sensitively at the Linear Collider (LC) via Higgs-strahlung process $e^+e^- \to Z^* \to Z + H$ with $Z \to f\bar{f}$. By our study, the bounds on $g^{(1)}_{HZZ}$ and $g^{(2)}_{HZZ}$ obtained through W^+W^+ scattering at the LHC could almost reach the same level of O (10^{-3} - 10^{-2}) TeV^{-1} as that obtained from the LC [1, 12].

TABLE VI: Number of events at the LHC, with an integrated luminosity of 300fb $^{-1}$, for $pp \to W^+W^+jj \to \ell^+\nu\ell^+\nu jj$ ($\ell^+ = e^+$ or μ^+) in the linearly realized effective Lagrangia with various values of m_H and f_W/Λ^2.

$m_H(GeV)$	$f_W/\Lambda^2(\mathrm{TeV}^{-2})$								
	-3.0	-2.0	-1.3	-1.0	0.0	0.9	1.1	2.0	3.0
115	70	38	18	14	9	14	18	45	78
130	70	38	18	14	9	14	18	45	79
200	72	38	18	14	9	14	18	46	79
300	73	39	19	15	9	15	19	47	80

V. CONCLUSIONS

The process $pp \to W^+W^+jj \to \ell^+\nu\ell^+\nu jj$ is sensitive for testing anomalous HVV couplings in the linearly realized Higgs sector. The two parameters f_W and f_{WW} are studied separately neglecting the contributions of f_B and f_{BB}. The limits of $g^{(i)}_{HVV}$, i=1, 2, are set as shown in Eqs. (13). If the SM is correct, the measurement on $g^{(i)}_{HWW}$ is two times more sensitive than that given in Ref. [1]. The bounds of $g^{(1)}_{HZZ}$ and $g^{(2)}_{HZZ}$ are at the level of (10^{-3} - 10^{-2}) TeV^{-1} which is almost at the same order predicted at the LC.

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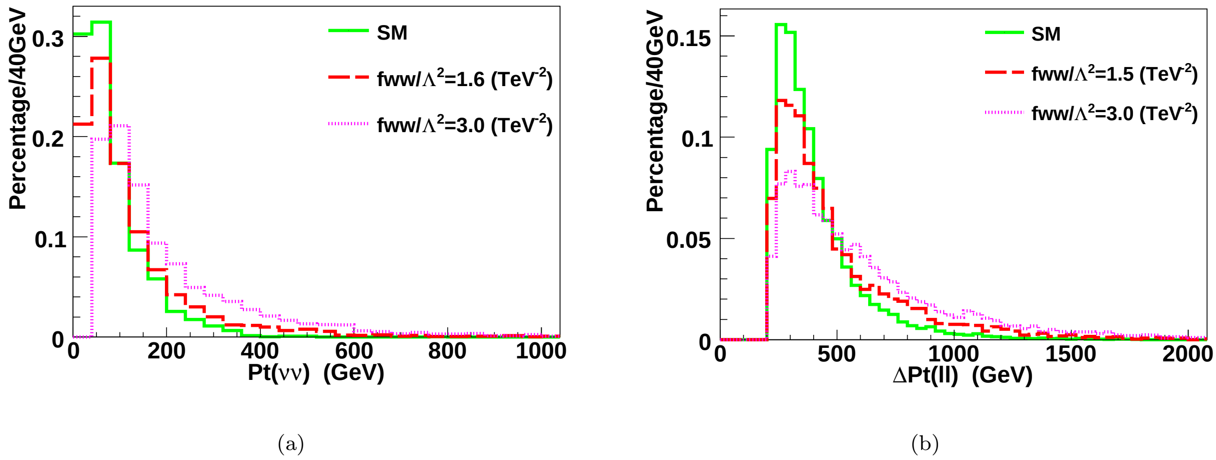
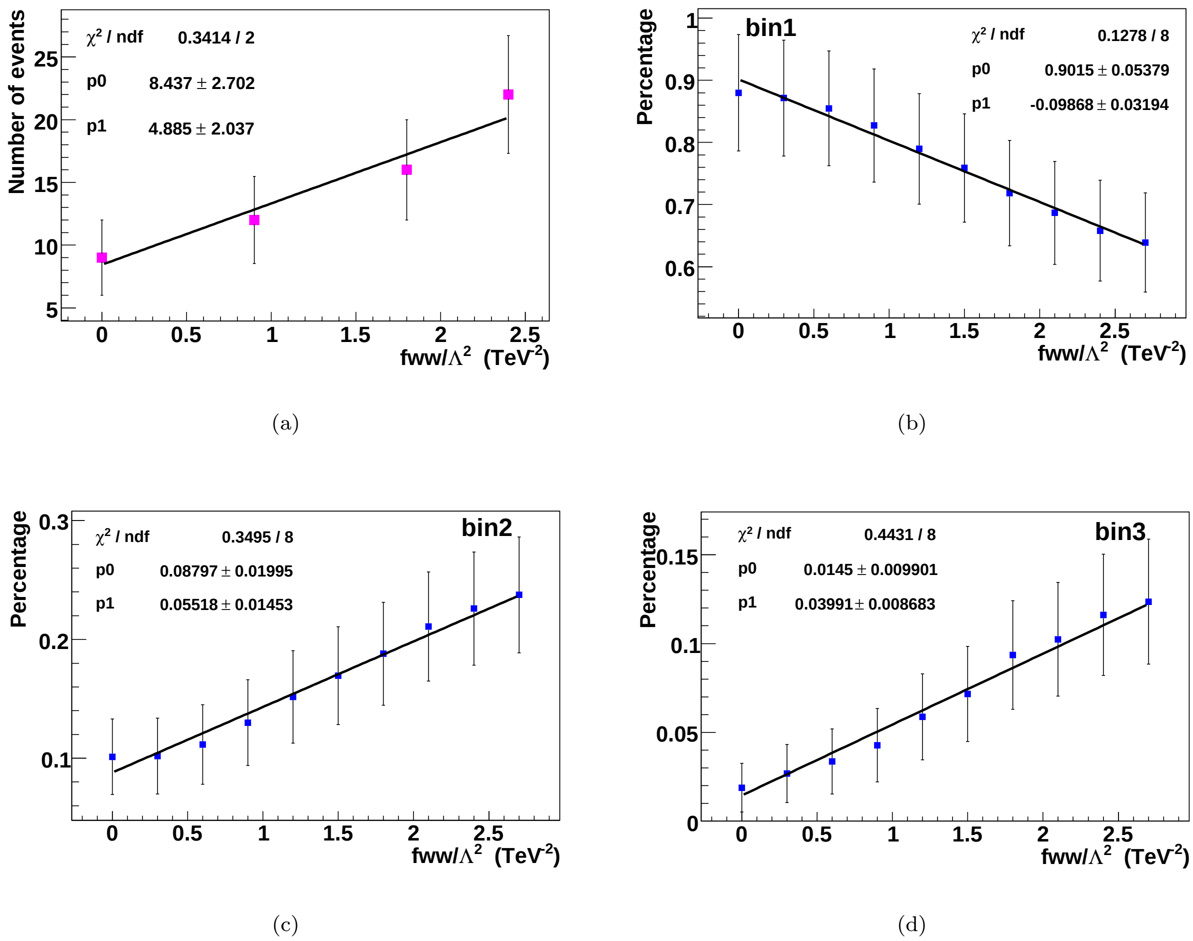


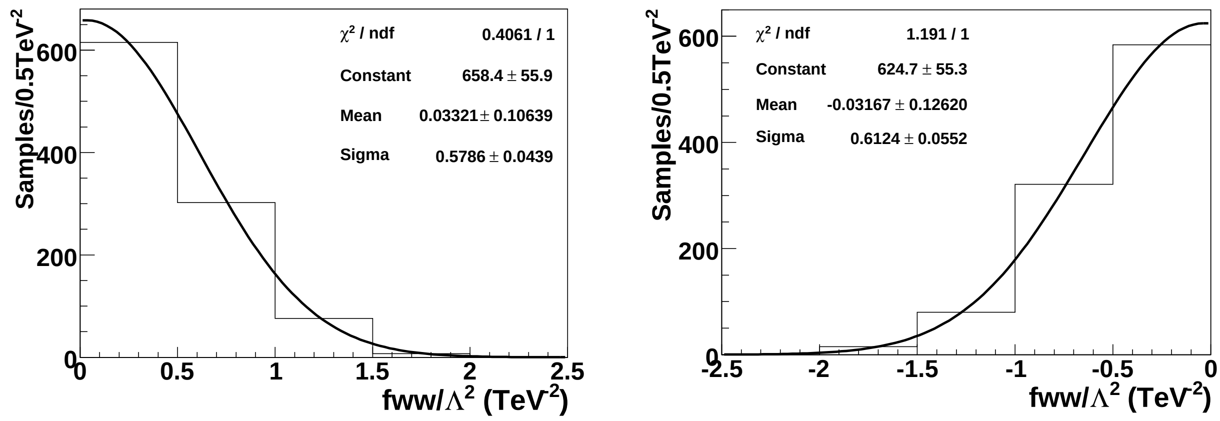
(a) (b)

FIG. 1: (a) The normalized distributions of $Pt(\nu\nu)$ with suggested cuts, (b) the normalized distributions of $\Delta Pt(\ell\ell)$ with optimized cuts.



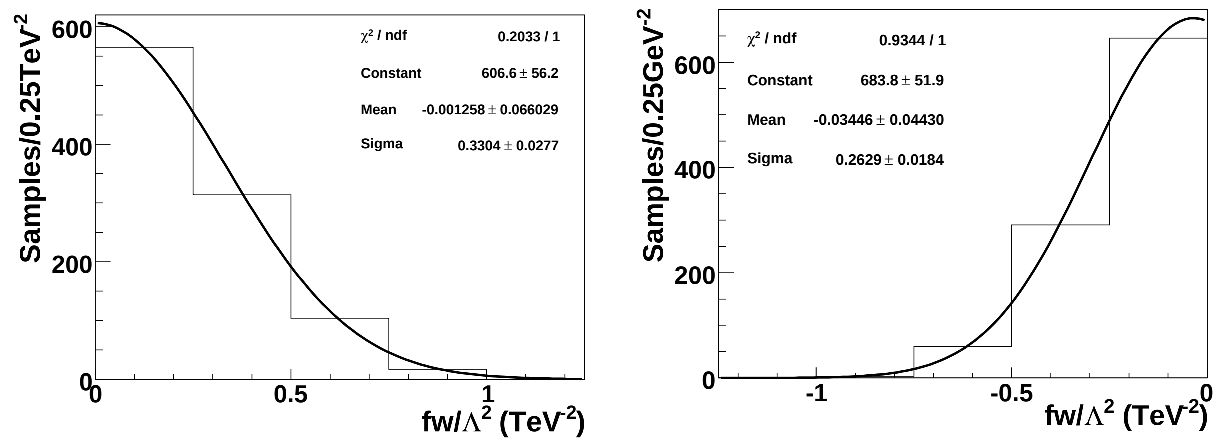
(a) (b) (c) (d)

FIG. 2: (a) The numbers of events, with integrated luminosity of 300 fb^{-1}, as a function of f_{WW}/Λ^2. Histograms (b) (c) (d) show the percentage of events in bin1, bin2 and bin3, for various f_{WW}/Λ^2 values.



(a) (b)

FIG. 3: (a) (b) The extracted f_{WW}/Λ^2's distribution via maximum likelihood fit for 1000 SM samples and results of fitting the distributions with Gaussian Functions are shown separately for plus and minus sides.



(a) (b)

FIG. 4: (a) (b) The extracted f_W/Λ^2's distribution via maximum likelihood fit for 1000 SM samples and results of fitting the distributions with Gaussian Functions are shown separately for plus and minus sides.