Measuring the ratio of HWW and HZZ couplings through W^+W^-H production

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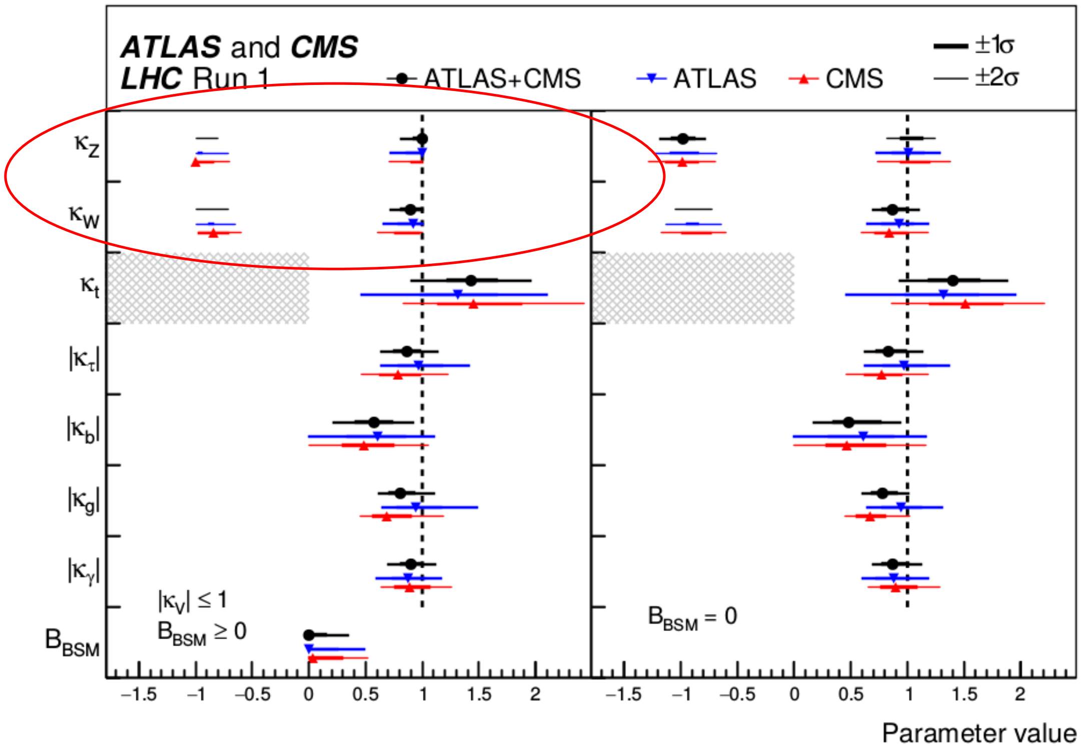
arXiv: 1805.01689, JHEP 1808 (2018) 126

Workshop "Beyond the SM"

Oct. 2, 2018

Higgs measurements

SM(-like) Higgs boson



In κ-framework

$$\kappa_j^2 = \sigma_j / \sigma_j^{\rm SM} \quad \text{or}$$

$$\kappa_j^2 = \Gamma^j / \Gamma^j_{\rm SM}$$

LHCHXSWG, 1307.1347

JHEP 1608 (2016) 045

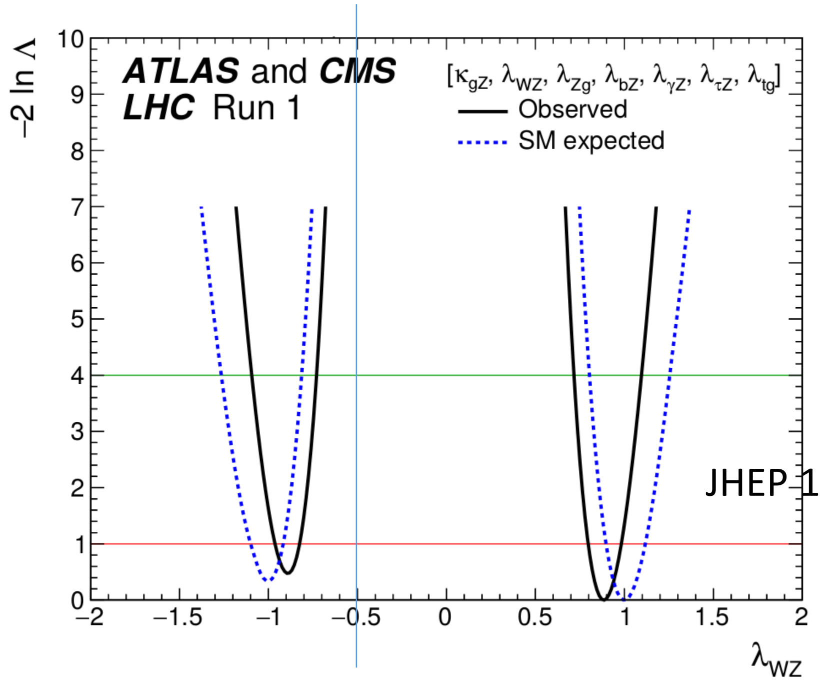
care more about

κ_W, κ_Z

$$g_{HWW} = \kappa_W g_{HWW}^{SM}, g_{HZZ} = \kappa_Z g_{HZZ}^{SM}$$

Ratio of HWW and HZZ couplings

$$\boxed{\lambda_{WZ} \equiv \kappa_W / \kappa_Z}$$



JHEP 1608 (2016) 045

The allowed regions by experimental measurements are two-fold

Ratio of HWW and HZZ couplings

At the tree-level in the SM

(1) $$\rho \equiv \frac{m_W^2}{m_Z^2 \cos^2\theta_W} = 1$$

Exp: $\rho_0 = 1.00039 \pm 0.00019$

PDG 2018

(2) $$\frac{g_{HWW}^{\rm SM}}{g_{HZZ}^{\rm SM}\cos^2\theta_W} = 1$$

Exp: negative region can not be excluded by considered signal strength measurements

(1) and (2) are not necessarily correlated

For example, in the Georgi-Machacek model,

H. Georgi and M. Machacek, Nucl. Phys. B262, 463 (1985)

$\rho = 1$ (custodial symmetry),

λ_{WZ}=1,-1/2

Ratio of HWW and HZZ couplings

SM + complex triplet + real triplet & custodial symmetry

H. Georgi and M. Machacek, Nucl. Phys. B262, 463 (1985).

$\rho = 1$, λ_{WZ}=1,-1/2

A realistic model: J.-Y. Cen, J.-H. Chen, X.-G. He, J.-Y. Su, 1803.05254

SM + complex triplet + real triplet & $\rho = 1$

$$\lambda_{WZ}^{h_1^m} = 1 - \frac{2v_\chi(\sqrt{2}\cos\gamma + \sin\gamma)}{v_H \cot\alpha + 4v_\chi \sin\gamma},$$
$$\lambda_{WZ}^{h_2^m} = 1 + \frac{2v_\chi(\sqrt{2}\cos\gamma + \sin\gamma)}{v_H \tan\alpha - 4v_\chi \sin\gamma},$$
$$\lambda_{WZ}^{h_3^m} = \frac{1}{2} + \frac{1}{\sqrt{2}}\tan\gamma .$$

$$\begin{pmatrix} h_H \\ h_\xi \\ h_\chi \end{pmatrix} = \begin{pmatrix} \cos\alpha & \sin\alpha & 0 \\ -\cos\gamma\sin\alpha & \cos\gamma\cos\alpha & \sin\gamma \\ \sin\gamma\sin\alpha & -\sin\gamma\cos\alpha & \cos\gamma \end{pmatrix} \begin{pmatrix} h_1^m \\ h_2^m \\ h_3^m \end{pmatrix}$$

λ_{WZ} is generally arbitrary

In GM model, tan$\gamma = -\sqrt{2}$

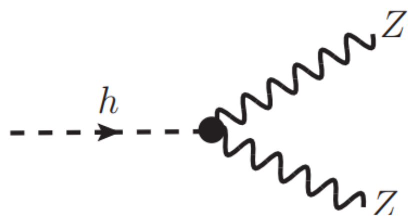
tree-loop interference

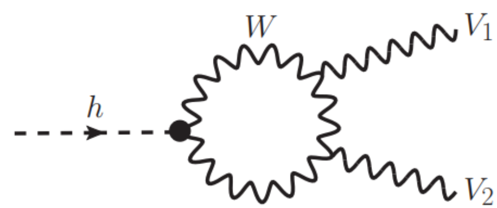
PRL **117**, 241801 (2016) PHYSICAL REVIEW LETTERS week ending 9 DECEMBER 2016

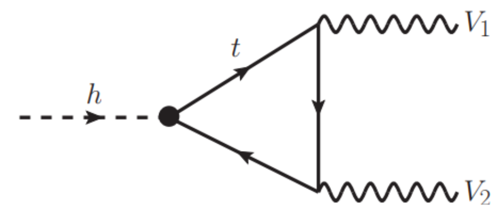
Golden Probe of Electroweak Symmetry Breaking

Yi Chen,[1,2,*] Joe Lykken,[3,†] Maria Spiropulu,[2,‡] Daniel Stolarski,[4,§] and Roberto Vega-Morales[5,‖]

through differential distribution of h-> 4l







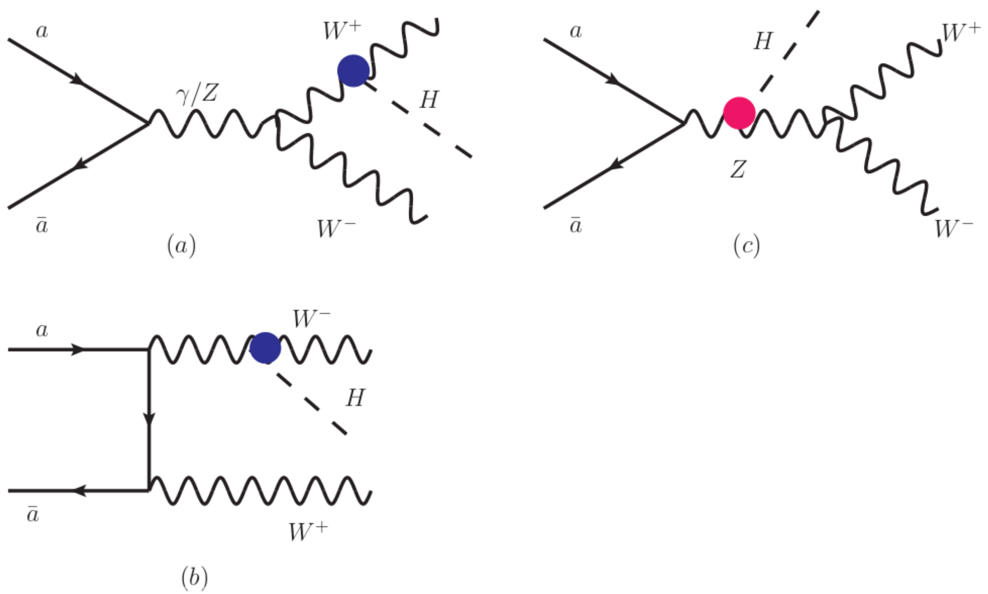
(1) assumption of the top quark Yukawa coupling
(2) more loop diagrams to keep gauge invariance
(3) kappa-framework is inconsistent for differential distributions

C. Mariotti, G. Passarino, 1612.00269

tree-tree interference

HWW and HZZ couplings can interfere at the tree-level

$$a\bar{a} \to W^+W^-H, a = q, e^-$$



taking m_H=125 GeV as an example

tree-tree interference

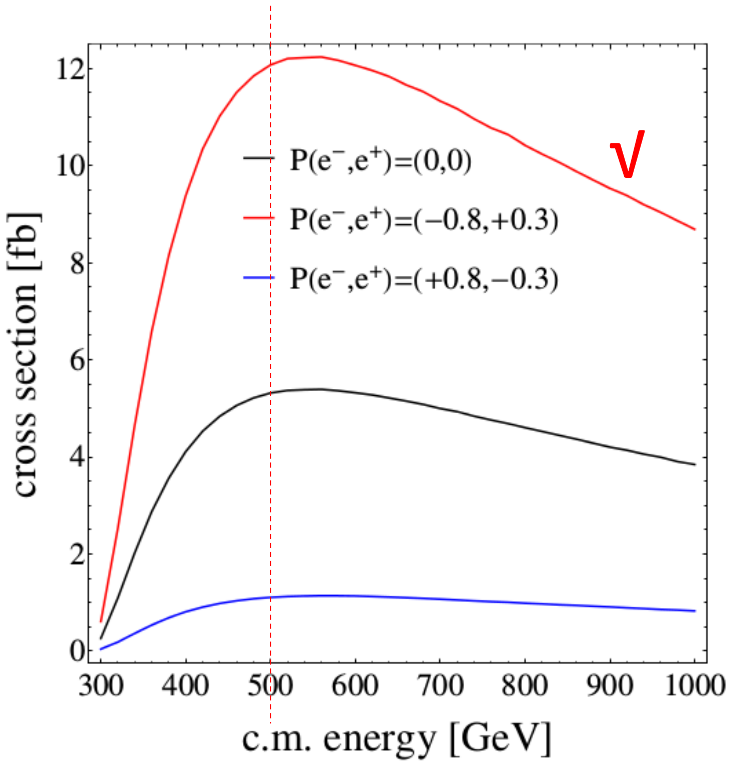
At the LHC: SM pp -> W+ W- H can not be discovered (below 2σ)

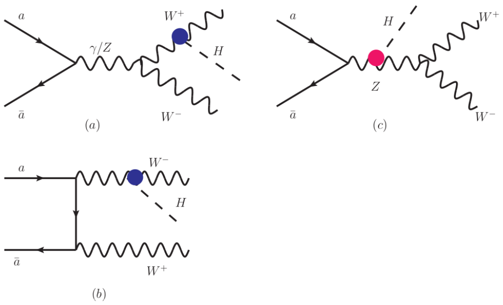
cross section (ab)	basic cuts	mjj-10	mjj-5	mll-25
W^+W^-H	8.648	7.413	6.882	5.296
$W^+W^+W^-W^-$	4.318	4.134	3.856	2.880
$jjW^\pm W^\pm W^\mp$	372.5	29.38	14.13	9.907
$W^+W^-Z(\ell^+\ell^-)$	472.1	(444.4)	(414.6)	4.107
$W^+W^-Z(\tau^+\tau^-)$	8.322	7.930	7.443	6.137
$jjW^\pm Z(\ell^+\ell^-)$	7.578×10^4	(7.187×10^4)	(3.616×10^4)	30.39
$t\bar{t}W^\pm$	803.9	70.90	34.16	24.68
$S/\sqrt{S+B}$ for 3 ab^{-1}	—	1.211	1.544	1.038

Table 1. Cut flow of the signal and background cross sections and the significances at the 13-TeV LHC. The b-tagging efficiency is assumed to be 70%.

tree-tree interference

At future electron-positron colliders:





$$|\mathcal{M}|^2 = |\mathcal{M}_W|^2 + |\mathcal{M}_Z|^2 + \mathcal{M}_{WZ}^2$$

$$\sigma_{\rm prod} = \kappa_W^2 \left[\sigma_W + \lambda_{WZ}^{-1}\sigma_{WZ} + \lambda_{WZ}^{-2}\sigma_Z\right]$$

$$\sigma_W = 13.54 \text{ fb}, \quad \sigma_Z = 1.015 \text{ fb}$$

$$\sigma_{WZ} = -2.555 \text{ fb}$$

Interference in the SM ($\lambda_{WZ} = 1$) is negative

Conventional approach

```
do kw=kw_min, kw_max, step_kw
    do kz=kz_min, kz_max, step_kz
       (1) generate p p > W+ W- H, W+ > l+ vl, W- > j j,  H > x y
       (2) impose cuts to suppress backgrounds
       (3) obtain the significance
       (4) obtain the sensitivity to the ratio
   end do
end do
Show plot of sensitivity
```

Collider analysis

Signal cross section after cuts:

$$\sigma_S = \kappa_W^2 \left(\sigma_W \epsilon_W + \lambda_{WZ}^{-1} \sigma_{WZ} \epsilon_{WZ} + \lambda_{WZ}^{-2} \sigma_Z \epsilon_Z\right) \mathcal{B} \qquad \mathcal{B} = \mathcal{B}(\kappa_W, \kappa_Z)$$

cut efficiencies are
independet of the branching ratios

we only need three benchmark scenarios:

$$\begin{aligned} &\text{BP1:} \quad \kappa_W = 1,\ \kappa_Z = 1, \\ &\text{BP2:} \quad \kappa_W = 1,\ \kappa_Z = -1, \\ &\text{BP3:} \quad \kappa_W = 1,\ \kappa_Z = 0. \end{aligned}$$

$$\begin{aligned} \epsilon_W &= \frac{\sigma_{\mathrm{BP3}} \epsilon_{\mathrm{BP3}}}{\sigma_W}, \\ \epsilon_{WZ} &= \frac{\sigma_{\mathrm{BP1}} \epsilon_{\mathrm{BP1}} - \sigma_{\mathrm{BP2}} \epsilon_{\mathrm{BP2}}}{2\sigma_{WZ}}, \\ \epsilon_Z &= \frac{\sigma_{\mathrm{BP1}} \epsilon_{\mathrm{BP1}} - \sigma_{\mathrm{BP3}} \epsilon_{\mathrm{BP3}}}{\sigma_Z} - \frac{\sigma_{\mathrm{BP1}} \epsilon_{\mathrm{BP1}} - \sigma_{\mathrm{BP2}} \epsilon_{\mathrm{BP2}}}{2\sigma_Z}. \end{aligned}$$

Collider analysis

G. Cowan, K. Cranmer, E. Gross, O. Vitells, Eur.Phys.J. C71 (2011) 1554

Discovery significance

$$S_D = \sqrt{2\left[(n_s + n_b)\ln\frac{n_s + n_b}{n_b} - n_s\right]},$$

Discrimination between $\lambda_{WZ} \neq 1$ and $\lambda_{WZ} = 1$

ratio test $\quad Q = -2\ln\frac{L(\lambda_0)}{L(1)}$

under the SM hypothesis

$$L(\lambda_{WZ}) = P(\text{data}|n_b + n_s^{\lambda_{WZ}}) \qquad \text{data} = n_b + n_s^{\lambda_{WZ}=1}$$

$\lambda_{WZ} = \lambda_0$ is rejected at the Z-sigma level with $Z = \Phi(1-p)^{-1}$

$$Z = \sqrt{2\left[\left(n_s^{\lambda_{WZ}=1} + n_b\right)\ln\frac{n_s^{\lambda_{WZ}=1} + n_b}{n_s^{\lambda_{WZ}=\lambda_0} + n_b} + \left(n_s^{\lambda_{WZ}=\lambda_0} - n_s^{\lambda_{WZ}=1}\right)\right]}.$$

Collider analysis

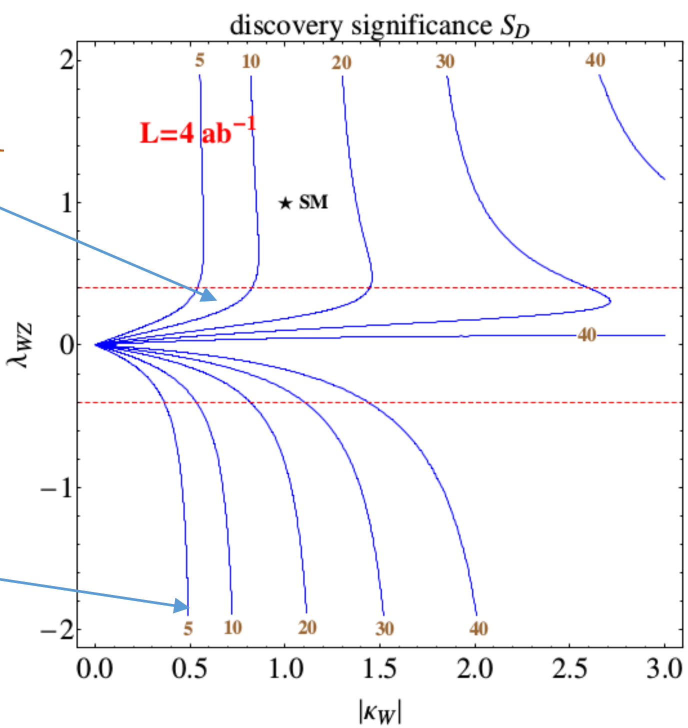
Higgs decay channel:

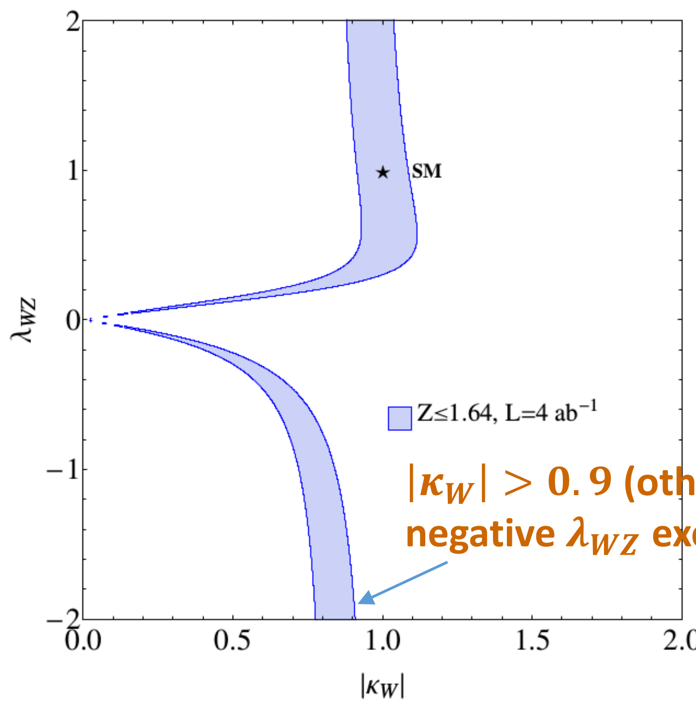
(1) H -> b b~ $$\mathcal{B} = \mathcal{B}_0 \frac{1}{\Gamma_H/\Gamma_H^0},$$

$$\Gamma_H = \Gamma_H^0\left[1 + (\kappa_W^2 - 1)\mathcal{B}^0_{HWW} + (\kappa_Z^2 - 1)\mathcal{B}^0_{HZZ}\right],$$

$\lambda_{WZ} < 0.41$

$|\kappa_W| > 0.6$





$|\kappa_W| > 0.9$ (other exps.), negative λ_{WZ} exclued

Collider analysis

Higgs decay channel:

(2) H -> W+ W-

$$\mathcal{B} = \mathcal{B}_0 \frac{\kappa_W^2}{\Gamma_H / \Gamma_H^0}$$

scheme A: couplings of H to SM fermions are the same as the SM Higgs boson
scheme B: H does not couple to the SM fermions at the tree-level

$$\Gamma_H = \begin{cases} \Gamma_H^0 \left[1 + \left(\kappa_W^2 - 1\right) \mathcal{B}_{HWW}^0 + \left(\kappa_Z^2 - 1\right) \mathcal{B}_{HZZ}^0\right], & \text{for scheme A,} \\ \Gamma_H^0 \left[\kappa_W^2 \mathcal{B}_{HWW}^0 + \kappa_Z^2 \mathcal{B}_{HZZ}^0\right], & \text{for scheme B.} \end{cases}$$

motivated by GM model

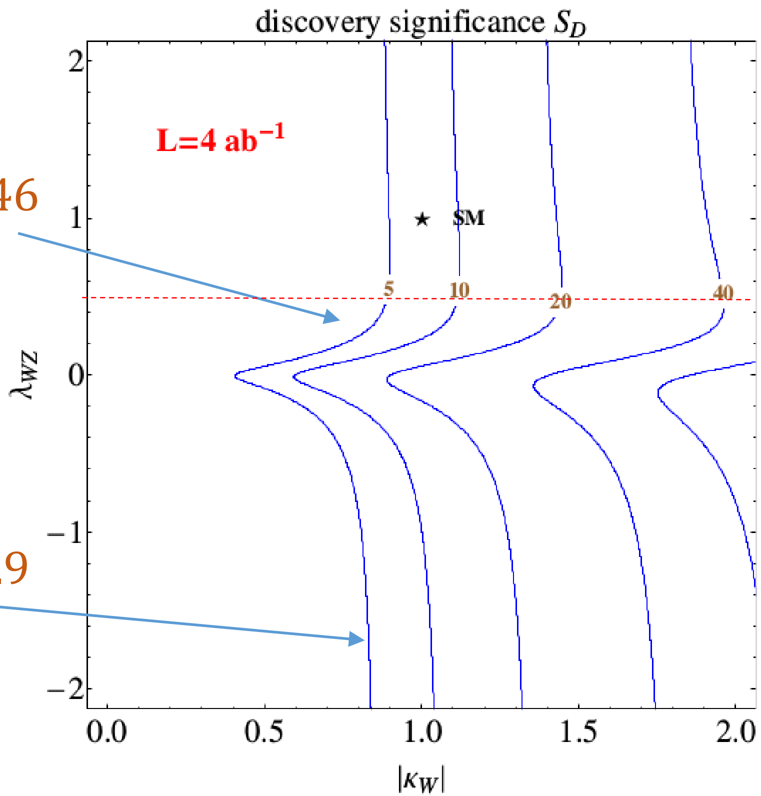
Collider analysis

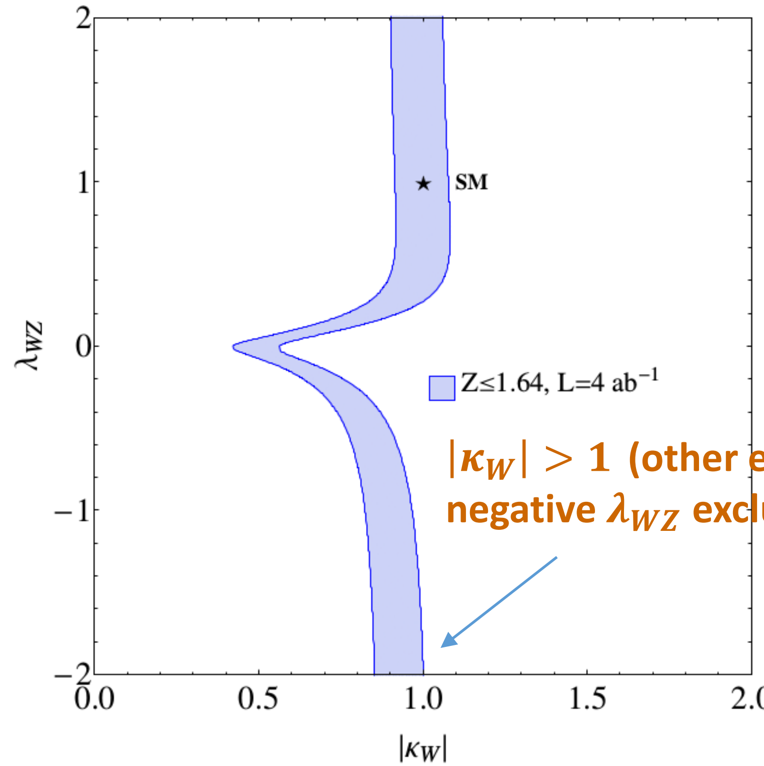
Higgs decay channel:

(2) H -> W+ W-   scheme A

$\lambda_{WZ} < 0.46$

$|\kappa_W| > 0.9$



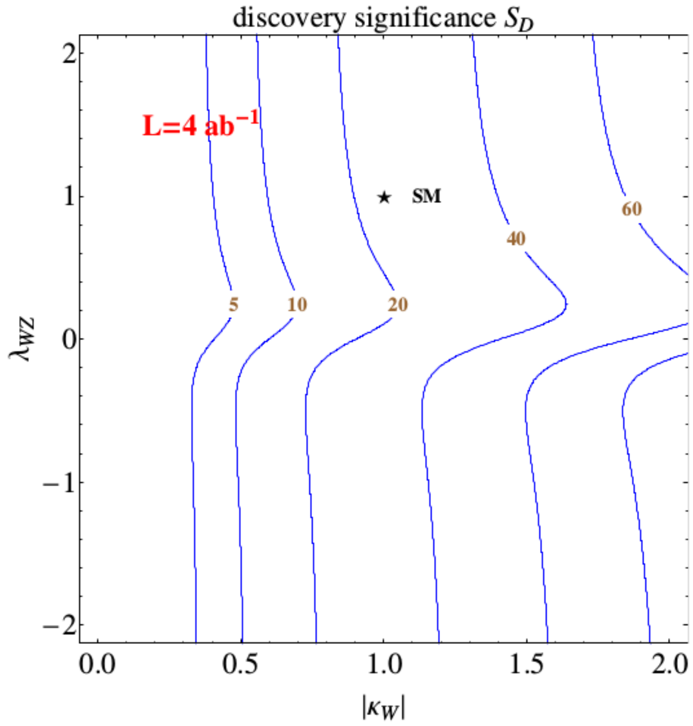


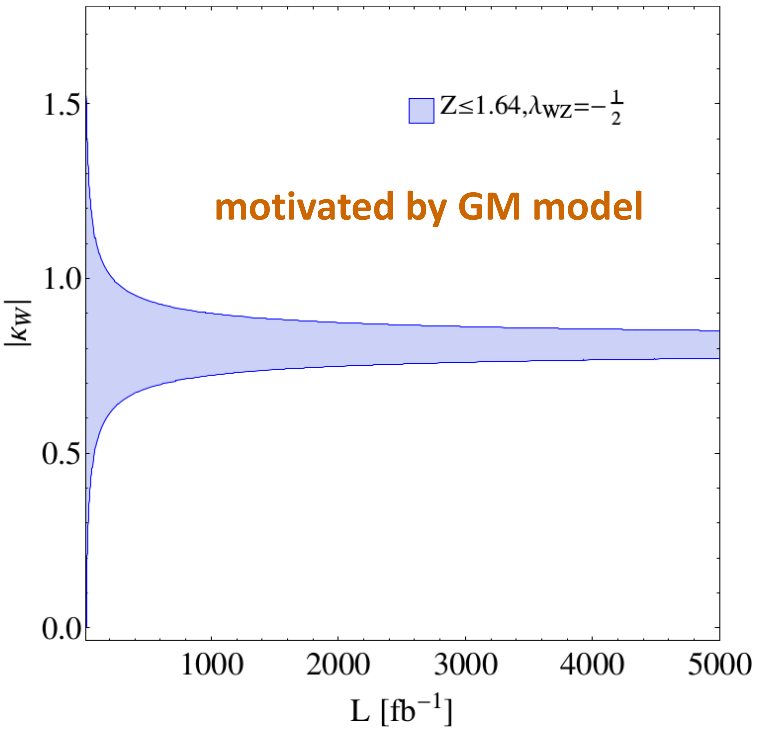
$|\kappa_W| > 1$ (other exps.), negative λ_{WZ} exclued

Collider analysis

Higgs decay channel:

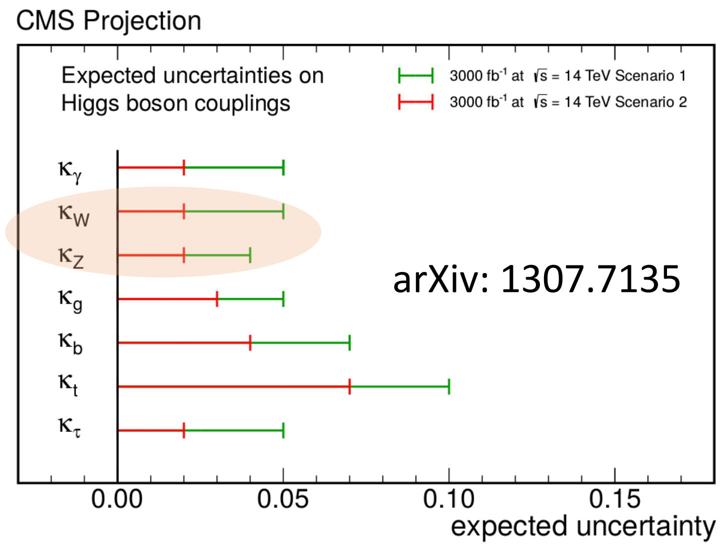
(2) H -> W+ W-   scheme B





Collider analysis

Improvement of precision measurement, which assumes that λ_{WZ} is close to 1



arXiv: 1307.7135

$$\delta\kappa_W/\kappa_W \leq 5\%, \quad \delta\kappa_Z/\kappa_Z \leq 4\%$$

$$\delta\lambda_{WZ}/\lambda_{WZ} \leq 6.4\%$$

(WWH@500)

$$\delta\lambda_{WZ}/\lambda_{WZ} = \sqrt{\frac{(\delta\sigma_S)^2 + (\partial\sigma_S/\partial\kappa_Z)^2(\delta\kappa_Z)^2}{(\partial\sigma_S/\partial\lambda_{WZ})^2\lambda_{WZ}^2}}$$

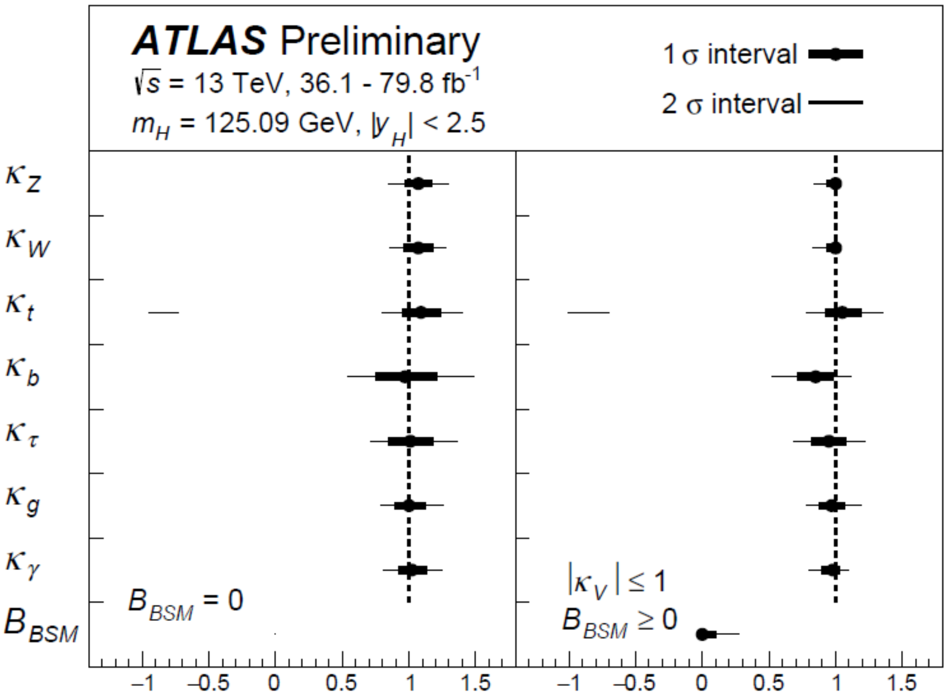
$+$ $\delta\kappa_Z/\kappa_Z \leq 4\%$ (HL-LHC) $\Rightarrow$ $\delta\lambda_{WZ}/\lambda_{WZ} < 0.063$ $\delta\lambda_{WZ}/\lambda_{WZ} < 0.071$

(H -> b b~) (H -> W+ W-)

Summary

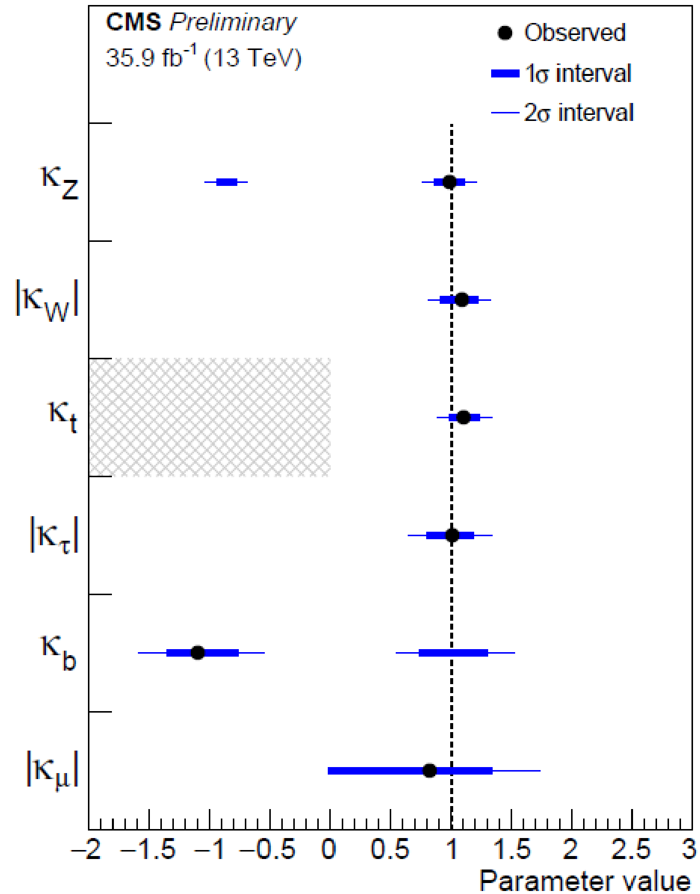
- Through W+W−H production, one can measure the ratio λ_{WZ} of HWW and HZZ couplings
- The discovery prospect and discrimination ability are studied
- Combined with measurements of HWW or HZZ coupling at HL-LHC, precision of λ_{WZ} can be 6.3%

Higgs measurements



All κs are assumed to be positive

ATLAS-CONF-2018-031



HIG-17-031-pas

Higgs measurements

Production	Loops	Interference	Effective scaling factor	Resolved scaling factor
$\sigma(ggF)$	✓	t–b	κ_g^2	$1.06 \cdot \kappa_t^2 + 0.01 \cdot \kappa_b^2 - 0.07 \cdot \kappa_t \kappa_b$
$\sigma(VBF)$	–	–		$0.74 \cdot \kappa_W^2 + 0.26 \cdot \kappa_Z^2$
$\sigma(WH)$	–	–		κ_W^2
$\sigma(qq/qg \to ZH)$	–	–		κ_Z^2
$\sigma(gg \to ZH)$	✓	t–Z		$2.27 \cdot \kappa_Z^2 + 0.37 \cdot \kappa_t^2 - 1.64 \cdot \kappa_Z \kappa_t$
$\sigma(ttH)$	–	–		κ_t^2
$\sigma(gb \to tHW)$	–	t–W		$1.84 \cdot \kappa_t^2 + 1.57 \cdot \kappa_W^2 - 2.41 \cdot \kappa_t \kappa_W$
$\sigma(qq/qb \to tHq)$	–	t–W		$3.40 \cdot \kappa_t^2 + 3.56 \cdot \kappa_W^2 - 5.96 \cdot \kappa_t \kappa_W$
$\sigma(bbH)$	–	–		κ_b^2
Partial decay width				
Γ^{ZZ}	–	–		κ_Z^2
Γ^{WW}	–	–		κ_W^2
$\Gamma^{\gamma\gamma}$	✓	t–W	κ_γ^2	$1.59 \cdot \kappa_W^2 + 0.07 \cdot \kappa_t^2 - 0.66 \cdot \kappa_W \kappa_t$

κ_t is involved in the determination of κ_W or κ_Z

Higgs decay channel:

(1) H -> b b~

TABLE I: Cut flow of signal and background cross sections in the $jj\ell^{\pm}bb$ channel.

cross section (fb)	basic cuts, b-tagged	m_{jj}	m_{bb}	p_T^{ℓ}
BP1	0.721	0.703	0.702	0.581
BP2	1.06	1.03	1.03	0.864
BP3	0.822	0.802	0.795	0.664
$t\bar{t}$	87.5	85.6	11.0	7.92
WWZ	1.09	1.07	0.0305	0.023

$$\epsilon_{\rm BP1} = 0.296 \quad \epsilon_{\rm BP2} = 0.308 \quad \epsilon_{\rm BP3} = 0.300.$$

$$\Rightarrow \quad \epsilon_W = 0.300, \quad \epsilon_Z = 0.346, \quad \epsilon_{WZ} = 0.337.$$

Collider analysis

Higgs decay channel:

(2) H -> W+ W-

TABLE II: Cut flow of the signal and background cross sections in the $\ell^\pm\ell^\pm\ell^\mp jj$ channel.

cross section (ab)	basic cuts	m_{jj}	$m_{\ell^+\ell^-}^{\rm SFOS}$
BP1	25.5	22.4	16.9
BP2	36.6	32.4	24.6
BP3	28.4	25.0	18.9
$4W$	4.92	4.57	3.04
$WWZ(\ell^+\ell^-)$	919	896	7.59
$WWZ(\tau^+\tau^-)$	9.53	9.35	6.85

$$\epsilon_{\rm BP1} = 0.243, \quad \epsilon_{\rm BP2} = 0.250, \quad \epsilon_{\rm BP3} = 0.242.$$

$$\epsilon_W = 0.242, \quad \epsilon_Z = 0.309, \quad \epsilon_{WZ} = 0.264.$$