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Determination of Higgs Couplings to Weak Bosons

Cheng-Wei Chiang
National Taiwan University

"My friend, we are in the peculiar position of not knowing what questions to ask. We are like little children playing cache-cache in the dark. We stretch out our hands and grope about."
— Hercule Poirot in *The ABC Murders*

An Extended Higgs Sector

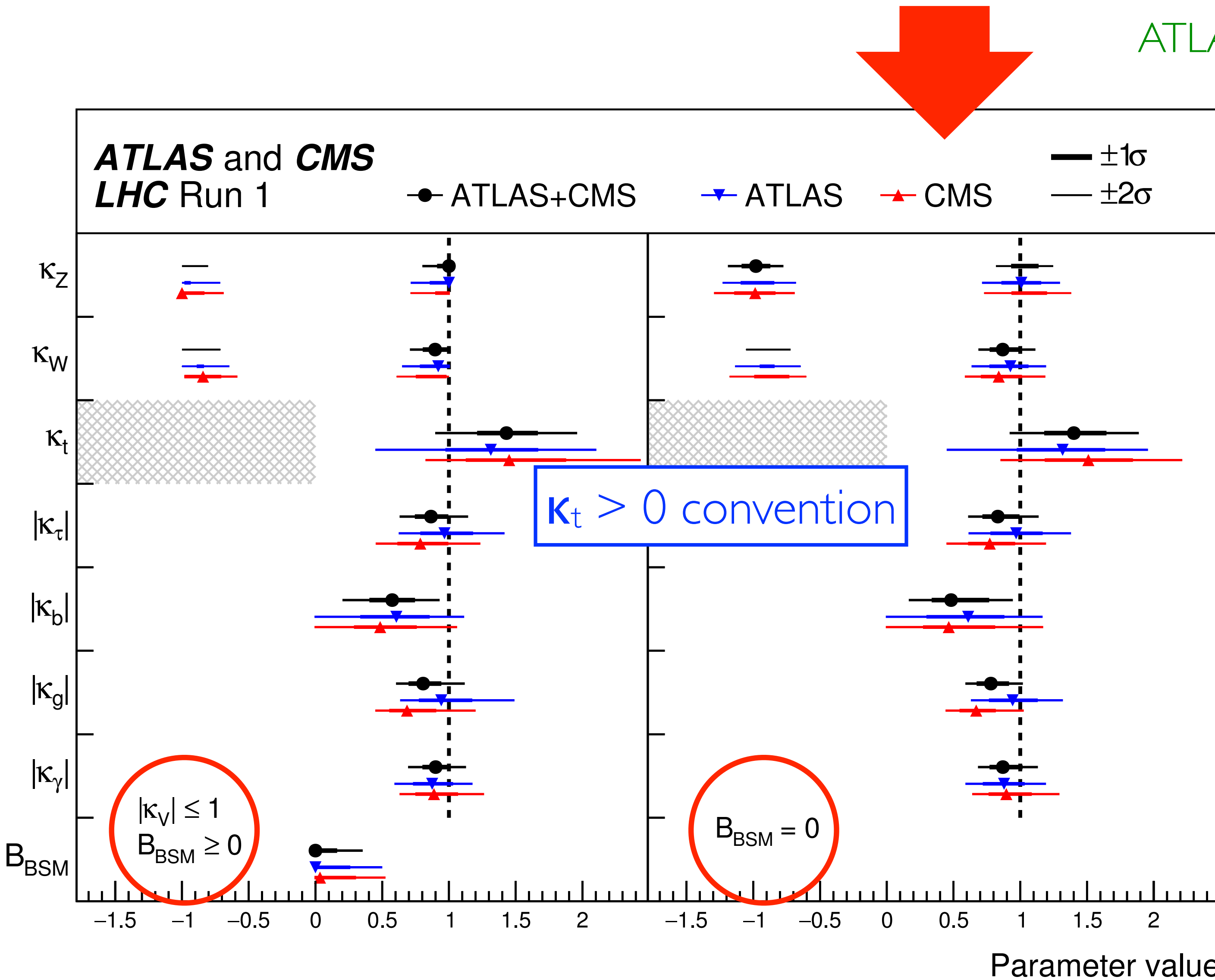
- The SM Higgs mechanism offers an elegant and minimal framework that achieves the required EWSB. But it does not forbid an extended Higgs sector.
- Other than usual symmetries, we have no guiding principles in constructing the scalar sector:
  - ➠ representations of scalar bosons
  - ➠ numbers of scalar bosons
  - ➠ extra symmetries (discrete/continuous/gauged)
  - ➠ required by new physics
    (neutrino mass, DM, EWBG, SUSY, etc)

cf. 3 generations of fermions and 3 gauge interactions

- For weak gauge bosons in such cases,
  - ➠ masses may involve different origins
  - ➠ couplings may be enhanced or weakened

LHC Run-I Data

ATLAS+CMS 2016



Recent Run-II Data

Parameter	ATLAS	CMS	Average
κ_W	1.07 ± 0.10	$1.12^{+0.13}_{-0.19}$	1.08 ± 0.08
κ_Z	1.07 ± 0.10	0.99 ± 0.11	1.03 ± 0.07

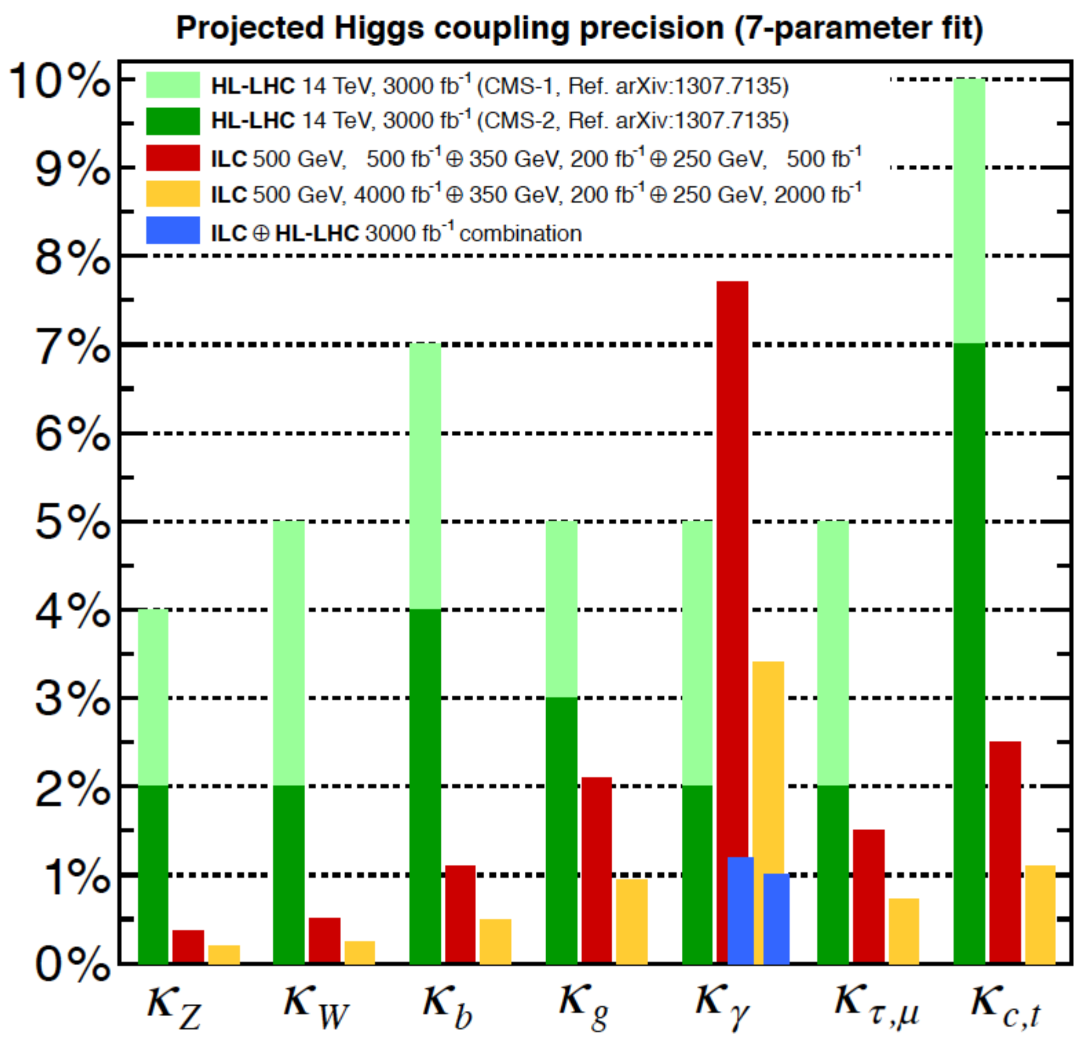
ATLAS+CMS 2018

- Concentrate on the central values.
- κ_W and/or κ_Z may be greater than 1.
- κ_W and κ_Z may be different. (CMS alone and central values only, by ~10%)

- What kind of Higgs sector features these properties?
- How different can κ_W and κ_Z be?

Expected Coupling Precision

- All Higgs couplings will be determined by HL-LHC + ILC to O(1) or sub percent level (particularly hVV couplings).



Fujii et al 2015

Higgs Extensions

- Higgs extensions are subject to a stringent constraint

$$\rho \equiv \frac{M_W^2}{M_Z^2 \cos^2\theta_W} = 1.00040 \pm 0.00024$$

PDG 2014

- In models with an extended Higgs sector, at tree level

$$\rho_{\rm tree} = \frac{\sum_i v_i^2 \left[T_i(T_i+1) - Y_i^2\right]}{\sum_i 2Y_i^2 v_i^2}$$

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$$\rho_{\text{tree}} = \frac{\sum_i v_i^2 \left[T_i(T_i+1) - Y_i^2\right]}{\sum_i 2Y_i^2 v_i^2}$$

- If only one new $SU(2)_L$ rep is added to the SM, $\rho_{\text{tree}} = 1$ gives the following possibilities, under $(SU(2)_L, U(1)_Y)$:
  (0,0) – real singlet, ➠ interacting mainly with h_{SM}
  (1/2,1/2) – doublet, ➠ a popular choice (e.g., 2HDM)
  (3,2) – septet,
  (25/2, 15/2), (48,28), (361/2,209/2), etc.

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- One can also choose to add a custodial symmetric rep (n,n) ($n \in \mathbb{N}$) under ($SU(2)_L$,$SU(2)_R$) with vacuum alignment.

➠ generalized Georgi-Machacek (GM) model Logan, Rentala 2015

➠ $n = 3$ is the original GM model

g_{HVV} in Some Models

Model	Higgs	$\kappa_V = g_{HVV}/g_{h_{\rm SM}VV}$	κ_W/κ_Z
rHSM	h	$\cos\alpha$	1
2HDM	h	$\sin(\beta-\alpha)$	1
	H	$\cos(\beta-\alpha)$	1
GM	h	$\sin\beta\cos\alpha - \sqrt{\frac{8}{3}}\cos\beta\sin\alpha$	1
	H_1^0	$\sin\beta\sin\alpha + \sqrt{\frac{8}{3}}\cos\beta\cos\alpha$	1
	H_3^0	0	—
	H_5^0	$\kappa_W = -\frac{\cos\beta}{\sqrt{3}}$ and $\kappa_Z = \frac{2\cos\beta}{\sqrt{3}}$	$-1/2$

κ's all normalized to corresponding SM values

$$\text{2HDM: } \tan\beta = \frac{v_u}{v_d} \quad \text{and} \quad \text{GM: } \tan\beta = \frac{v_\phi}{2\sqrt{2}v_\Delta}$$

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ATLAS+CMS 2018

- Concentrate on the central values.

✓ κ_W and/or κ_Z may be greater than 1.

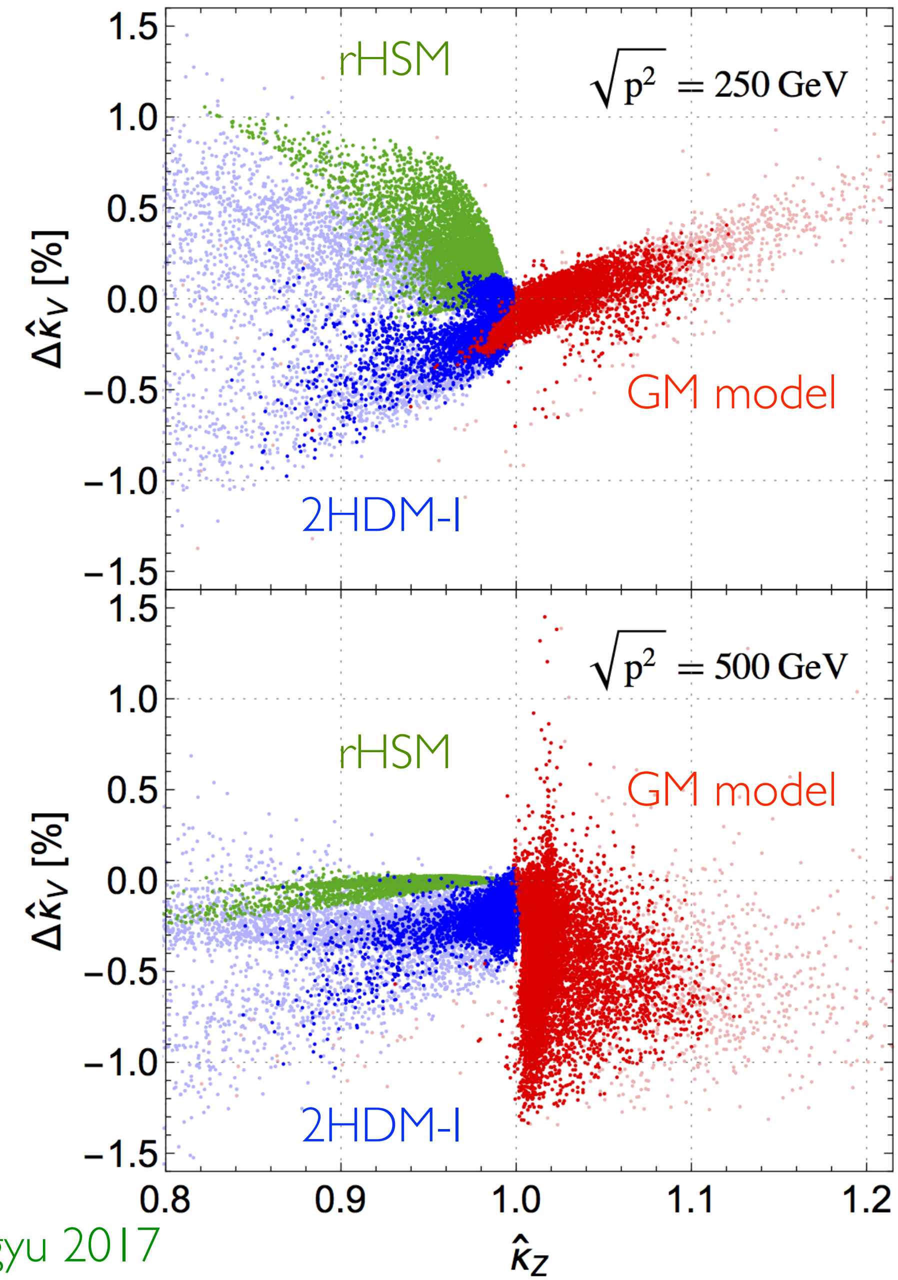
- κ_W and κ_Z may be different. (CMS alone and central values only, by ~10%)

- How much can $\kappa_W = \kappa_Z$ be violated by radiative corrections?
  ➠ model-dependent

1-Loop Results

$\Delta\hat{\kappa}_V \equiv \hat{\kappa}_W - \hat{\kappa}_Z$

- Lighter dots satisfy theoretical constraints (unitarity, stability, perturbativity, and oblique parameters [S and T]).
- Darker dots further satisfy Higgs signal strengths from LHC Run-I (20 channels). ATLAS+CMS 2016
- Other types of 2HDM are expected to have a similar result as 2HDM-I.
- It is possible to discriminate among the rHSM, 2HDMs and GM model.
- $\Delta\kappa_V \sim O(1\%)$ and may be observable.



CWC, Kuo, Yagyu 2017

Exotic Higgs Multiplets

- At least two active Higgs multiplets (X_1, X_2, …) larger than doublet are required, in addition to SM doublet Φ.
  ➠ consider simplest case with N = 2
- Suppose their quantum numbers are (T_1,Y_1) and (T_2,Y_2).
- The VEV of a complex (real) X_a is denoted by $v_a/\sqrt{2}$ (v_a).
- To have $\rho_{\rm tree} = 1$, the new VEVs have to satisfy

$$r \equiv \frac{v_2^2}{v_1^2} = -\frac{T_1(T_1+1)-3Y_1^2}{T_2(T_2+1)-3Y_2^2}$$

  with the total VEV

$$v^2 = v_\Phi^2 + \xi^2 v_1^2 \quad \text{with} \quad \xi^2 \equiv 4\left(Y_1^2 + rY_2^2\right)$$

- Define the mixing angle (analogous to 2HDM)

$$\tan\beta = \frac{v_\Phi}{\xi v_1}$$

Exotic Higgs Multiplets

- Tree-level unitarity of scattering processes requires that $T_a \leq 7/2$ (4) for a complex (real) scalar in the $N = 1$ case.
  ➠ used here as a conservative bound   Hally, Logan, Pilkington 2012
- In certain scenarios (often those with larger $SU(2)_L$ reps), electroweak couplings develop Landau poles below the Planck scale.
  ➠ always g at a lower scale than g'
- There could be accidental global U(1)'s associated with phase rotations of X_1 and X_2.
  ➠ at least one unwanted massless NG boson after EWSB
- Discard such scenarios, but otherwise impose no custodial symmetry on the Higgs potential.

Viable Scenarios

EW quantum #'s

CWC, Yagyu 2018

(T_1, Y_1)	$\geq$	(T_2, Y_2)	r	ξ^2	$v_1^{\max}$
(1,1)		(1,0)	1/2	4	118
(3/2,1/2)		(1,1)	3	13	65
(3/2,3/2)		(1,0)	3/2	9	79
(3/2,3/2)		(3/2,1/2)	1	10	75
(2,0)		(1,1)	6	24	48
(2,0)		(3/2,3/2)	2	18	56
(2,1)		(1,1)	3	16	59
(2,1)		(3/2,3/2)	1	13	65
(2,2)		(2,1)	2	24	48
(5/2, 1/2)		(1, 1)	8	33	41
(5/2, 1/2)		(3/2, 3/2)	8/3	25	47
(5/2, 3/2)		(1, 1)	2	17	57
(5/2, 3/2)		(3/2, 3/2)	2/3	15	61
(3,0)		(1,1)	12	48	34
(3,0)		(3/2,3/2)	4	36	39

GM model w/o custodial symmetry ➡ (1,1), (1,0)

demanding $y_t < \sqrt{4\pi}$ at electroweak scale ➡ lower bound on v_Φ

2 cases with r < 1

2 cases with r = 1

11 cases with r > 1

15 scenarios allowed

septet at most

Neutral Higgs Mixing

- Neutral components of Φ, X_1, and X_2 mix in a general way:

physical states ↓ original fields ↓

$$\begin{pmatrix} h \\ H_1 \\ H_2 \end{pmatrix} = R \begin{pmatrix} \Phi^0 \\ X_1^0 \\ X_2^0 \end{pmatrix}$$

↑ orthogonal rotation matrix

- Since only Φ couples to SM fermions, the scale factor for Yukawa couplings is universally given by

$$\kappa_F = \frac{R_{11}}{s_\beta} \quad \Rightarrow \quad R_{11} = \kappa_F s_\beta$$

mixing matrix element R_{11} in terms of κ_F and β.

Prediction of κ_W and κ_Z

- For W and Z:

$$\kappa_W = s_\beta R_{11} + c_\beta \frac{2[T_1(T_1+1) - Y_1^2]R'}{\xi} c_\theta + c_\beta \sqrt{r} \frac{2[T_2(T_2+1) - Y_2^2]R'}{\xi} s_\theta$$

$$\kappa_Z = s_\beta R_{11} + c_\beta \frac{4Y_1^2 R'}{\xi} c_\theta + c_\beta \sqrt{r} \frac{4Y_2^2 R'}{\xi} s_\theta$$

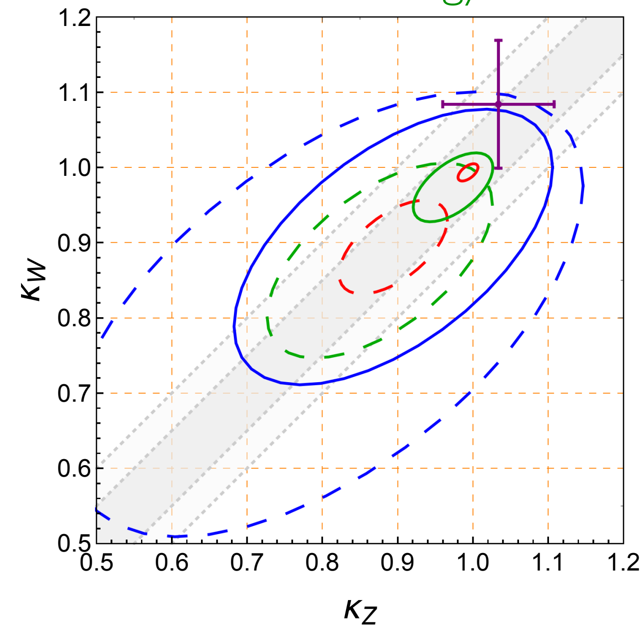
$$R' \equiv \sqrt{1 - R_{11}^2}$$

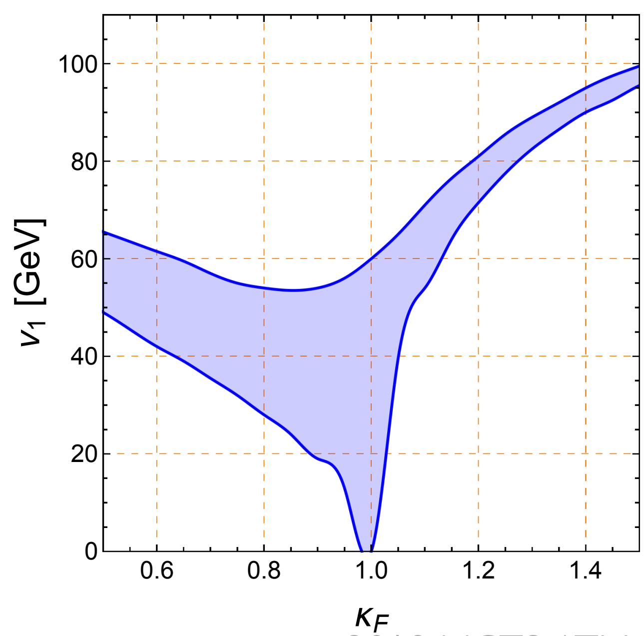
- Custodial relation $\kappa_W = \kappa_Z$ occurs when $\tan\theta = -\sqrt{r}$, a special mixing angle related to the ratio of exotic VEV's.

Numerical Result

- Take first scenario as an example.
- Correlation plot for κ_F = 0.9 (dashed) and 1.0 (solid) with v_1 = 10 (red), 20 (green) and 40 GeV (blue), by scanning all mixing angle θ.
- The dark (light) gray band indicates $|\kappa_Z - \kappa_W| \leq 5\%$ (10%).
- The purple cross marks current data.
- Blue region allowed by current data of $\kappa_{W,Z}$ at 1σ level.
- Except for the limit where κ_F is SM-like, there generally exist upper and lower bounds on v_Δ.

CWC, Yagyu 2018





g_{HWW}/g_{HZZ}

- The ratio

$$\lambda_{WZ} \equiv g_{HWW}/g_{HZZ}$$

for the SM Higgs boson is +1 at tree level.

- This may not be true for exotic Higgs bosons.

➠ e.g., –1/2 for H_5^0 in the GM model

- For the 125-GeV Higgs,

$$-1.10 \lesssim \lambda_{WZ} \lesssim -0.73 \quad \text{or} \quad 0.72 \lesssim \lambda_{WZ} \lesssim 1.10 \quad \text{(Run-I)}$$

$$-1.39 \lesssim \lambda_{WZ} \lesssim -0.97 \quad \text{or} \quad 0.92 \lesssim \lambda_{WZ} \lesssim 1.37 \quad \text{(Run-II, 35.9/fb)}$$

➠ a two-fold ambiguity in such measurements

- With 3/ab, the HL-LHC is anticipated to achieve

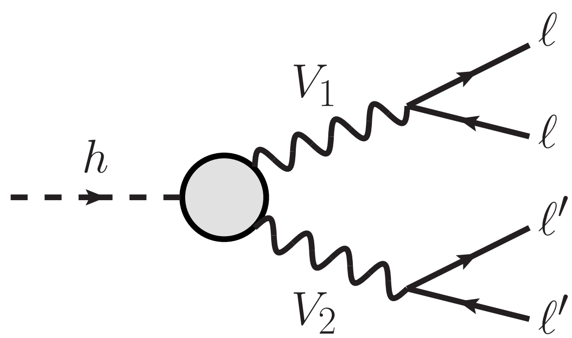
$$|\delta\kappa_W/\kappa_W| \le 5\% \quad , \quad |\delta\kappa_Z/\kappa_Z| \le 4\%$$

$$\Rightarrow \ |\delta\lambda_{WZ}/\lambda_{WZ}| \le 6.4\%$$

assuming that the central values remain SM-like.

Solving the Ambiguity

- How can we experimentally determine this ratio, including its sign?
- It can be measured in the differential distribution of H → ZZ* → 4ℓ due to the interference between amplitudes at tree and one-loop levels, which are proportional to the HZZ and HWW couplings, respectively.



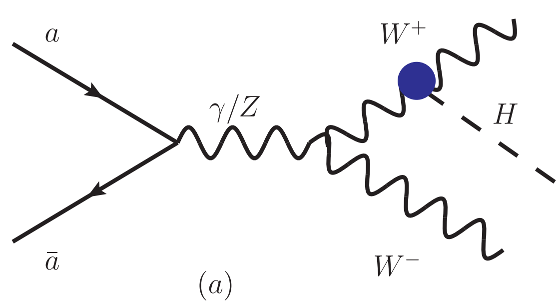
Chen, Lykken, Spiropulu, Stolarski, Vega-Morales 2016

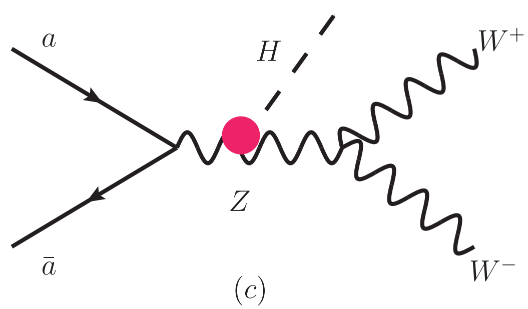
FIG. 1. Schematic representation of the hVV contributions to the $h \to 4\ell$ amplitude where $V_{1,2} = Z, \gamma$ and $\ell, \ell' = e, \mu$.

- However, this is more technically involved due to issues such as gauge invariance, scheme/scale dependence.

Solving the Ambiguity

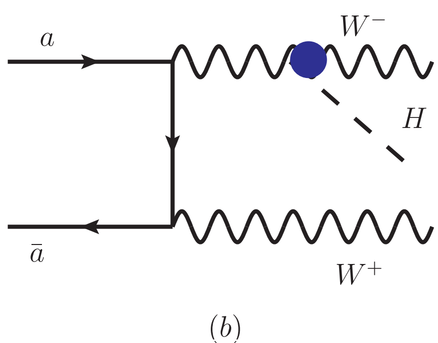
- How can we experimentally determine this ratio, including its sign?
- We propose to consider $e^+e^- \to W^+W^-H$ process (conceptually much simpler than Chen et al), where a desirable interference occurs among the tree-level amplitudes and allows us to experimentally fix λ_{WZ}.





CWC, He, Li 2018

- H here is not limited to SM-like Higgs boson
- Use 125-GeV Higgs as an explicit example

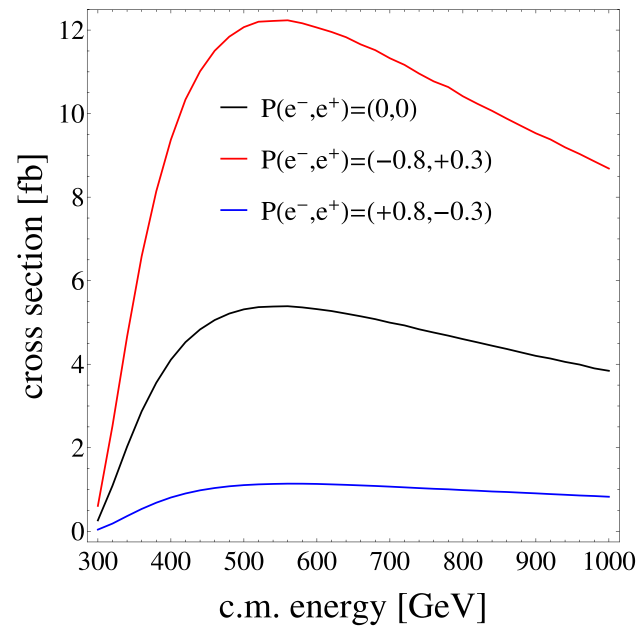


$$\sigma_{\rm prod} = \kappa_W^2 \left[\sigma_W + \lambda_{WZ}^{-1}\sigma_{WZ} + \lambda_{WZ}^{-2}\sigma_Z\right]$$

Cross Section @ ILC

CWC, He, Li 2018

- Cross section of $e^+e^- \to W^+W^-H$ as a function of colliding energy for different polarization schemes.
  ➠ preferring 500-GeV ILC with $P(e^-,e^+) = (-0.8,+0.3)$ 1306.6352 [hep-ex]
  ➠ peak position may change for a different Higgs boson



- We consider the above scheme with an integrated luminosity $L = 4$ /ab:

1506.05992 [hep-ex]
1506.07830 [hep-ex]

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

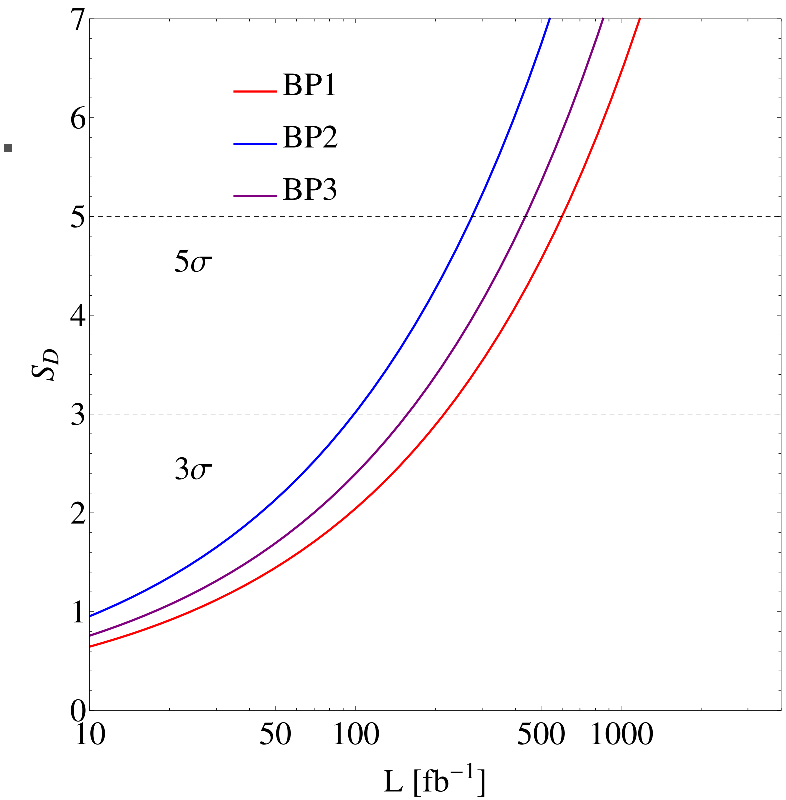
$$\sigma_W = 13.54\text{fb}, \quad \sigma_Z = 1.015\text{fb}, \quad \sigma_{WZ} = -2.555\text{fb}$$

- $\sigma_W > \sigma_Z$ by one order of magnitude
- destructive interference if λ_{WZ} is positive

THE $e^+e^- \to W^+W^-H \to jj\ell^{\pm}\nu bb$ PROCESS

CWC, He, Li 2018

- Consider $e^+e^- \to W^+W^-H$, with one $W \to \ell\nu$, the other $W \to jj$, and $H \to b\underline{b}$.
- 5σ discovery achieved with L = (600/fb, 300/fb, 450/fb) for (BP1, BP2, BP3), respectively.
- BP1 requires the largest luminosity due to the **smallest** cross section from **destructive interference**.
- Assume SM-like Hff couplings.
- H→WW* scenario also considered. ➠ see our paper

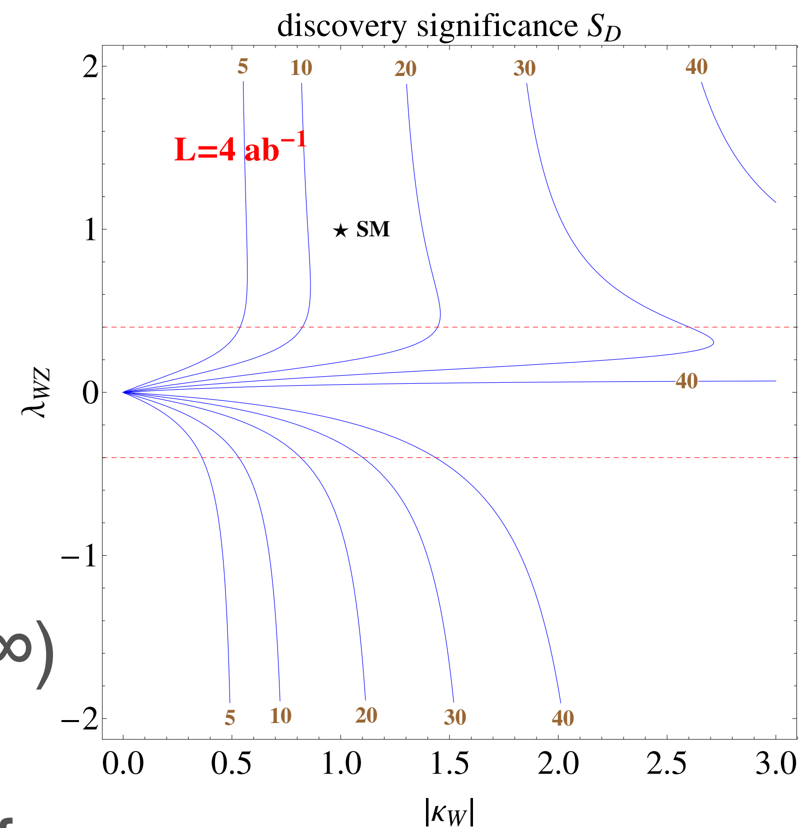


signal significance as a function of L

$$\text{BP1:} \quad \kappa_W = 1, \ \kappa_Z = 1 \ \text{(SM)}$$
$$\text{BP2:} \quad \kappa_W = 1, \ \kappa_Z = -1$$
$$\text{BP3:} \quad \kappa_W = 1, \ \kappa_Z = 0.$$

The $e^+e^- \to W^+W^-H \to jj\ell^\pm\nu bb$ Process

- Contours of signal significance for L = 4/ab.
- Discoverable for $|\kappa_W| \gtrsim 0.6$, irrespective of the value of λ_{WZ}.
- More sensitive to scenarios with $|\lambda_{WZ}| \lesssim 0.4$ as σ_{WZ} becomes less important than σ_Z. ($\lambda_{WZ} \to 0 \Rightarrow \kappa_Z \to \infty$)
- By combining this cross section measurement and measurement of $|\kappa_W|$ at HL-LHC, it is straightforward to determine λ_{WZ} (magnitude and sign) at a high precision.



- Similar processes at LHC under study.

Summary

- Knowledge of $\kappa_{W,Z}$ is crucial for our understanding of EWSB and the Higgs sector.
- Current data show some hint of "non-standard" $\kappa_{W,Z}$:
  (1) either one could be greater than 1; and
  (2) they could be different from each other.
  ➠ exhausted simplest Higgs sectors with such features
  ➠ give quantitative predictions about their values
- It is experimentally possible determine magnitudes and relative sign of $\kappa_{W,Z}$ through interference in $e^+e^- \to HW^+W^-$ process.
  ➠ possibility at LHC being studied now