HPNP2019 The 4th International Workshop on "Higgs as a Probe of New Physics"

18.-22. February 2019, Osaka University, Japan

Determination of Higgs Couplings to Weak Bosons

CWC, K Yagyu, Phys.Lett. B786 (2018) 268
CWC, X.G. He, G. Li, JHEP 1808 (2018) 126

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*

Outline

- Motivations
- Exotic models with $\kappa_W \neq \kappa_Z$
- Determination of κ_W/κ_Z (at ILC)
- Summary

An Extended Higgs Sector

- The SM Higgs mechanism offers an elegant and minimal framework that achieves the required EWSB.
- Just to break the EW symmetry, one can employ nontrivial Higgs representations other than the doublet (though the choice of doublet is economic for fermion mass).
- For W and Z in cases where more Higgs fields participate in EWSB,
  ➠ masses involve different origins
  ➠ couplings with H(125) may be modified and/or different
  ➠ HWW and HZZ couplings (or κ_W and κ_Z) being fundamental in EWSB and indicators the custodial symmetry

Salient Features of SM

- Due to custodial symmetry, interactions between Higgs and weak gauge bosons dictate that at tree level

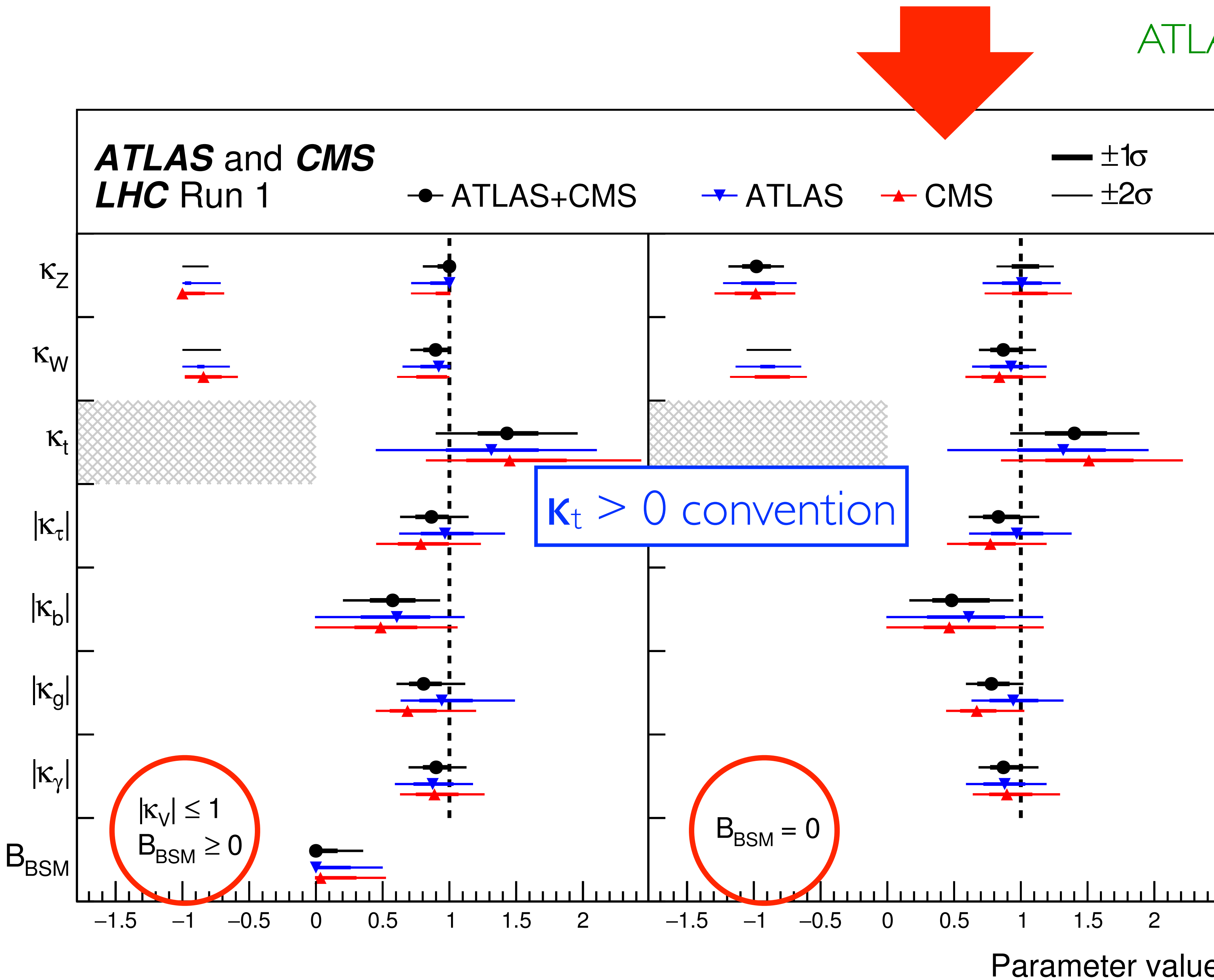
$$\rho \equiv \frac{M_W^2}{M_Z^2 \cos^2\theta_W} = 1$$

$$\kappa_W = \kappa_Z = 1$$

- How can we deviate from these predictions provided data show otherwise?
- What kind of exotic Higgs extensions can we go after?

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-CONF-2018-31 (13 TeV, 80/fb)
CMS-PAS-HIG-17-031 (13 TeV, 36/fb)

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

- What kind of (minimally extended) Higgs sector features these properties?
- How different can κ_W and κ_Z be?
- Confine ourselves to only extending the Higgs sector.

Higgs Extensions

- Higgs extensions are subject to a stringent constraint

$$\rho_{\rm exp} = 1.00039 \pm 0.00019$$

PDG 2018

- 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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- If only one new $SU(2)_L$ rep is added to the SM, $\rho_{\rm tree} = 1$ 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), etc ➠ disfavored by unitarity bound

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

  ➠ generalized Georgi-Machacek (GM) model

  ➠ n = 3 is the original GM model

Logan, Rentala 2015

Higgs Extensions

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- Simplest CP-conserving custodial Higgs models:
  - real Higgs singlet model (rHSM): Φ + S
  - two Higgs doublet model (2HDM): Φ + Φ'
  - GM model: Φ + Δ
  - will make a comparison of them in hVV couplings.

g_{HVV} in Simple Models

Model	Higgs	$\kappa_V = g_{HVV}/g_{h_{SM}VV}$	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 $\kappa_Z = \frac{2\cos\beta}{\sqrt{3}}$	$-1/2$

SM-like Higgs

≤ 1

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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- 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

κ_Z AND κ_W

- hVV scale factors at 1-loop with momentum dependence are defined as:

momentum of off-shell V^*

$$\hat{\kappa}_V(p^2) \equiv \frac{\hat{\Gamma}_1(m_V^2, p^2, m_h^2)_{\rm NP}}{\hat{\Gamma}_1(m_V^2, p^2, m_h^2)_{\rm SM}}$$

- At 1σ, $\kappa_{W,Z}$ are (will be) determined to be

LHC Run-I	$\kappa_Z = [0.94, 1.13]$	$\kappa_W = [0.78, 1.00]$	
HL-LHC	$\Delta\kappa_Z = 2 - 4\%$	$\Delta\kappa_W = 2 - 5\%$	14 TeV, 3000/fb
ILC	$\Delta\kappa_Z = 0.58\%$	$\Delta\kappa_W = 0.81\%$	500 GeV, 500/fb ⊕ 350 GeV, 200/fb ⊕ 250 GeV, 500/fb

1606.02266 [hep-ex]
1310.8361 [hep-ex]
1506.05992 [hep-ex]

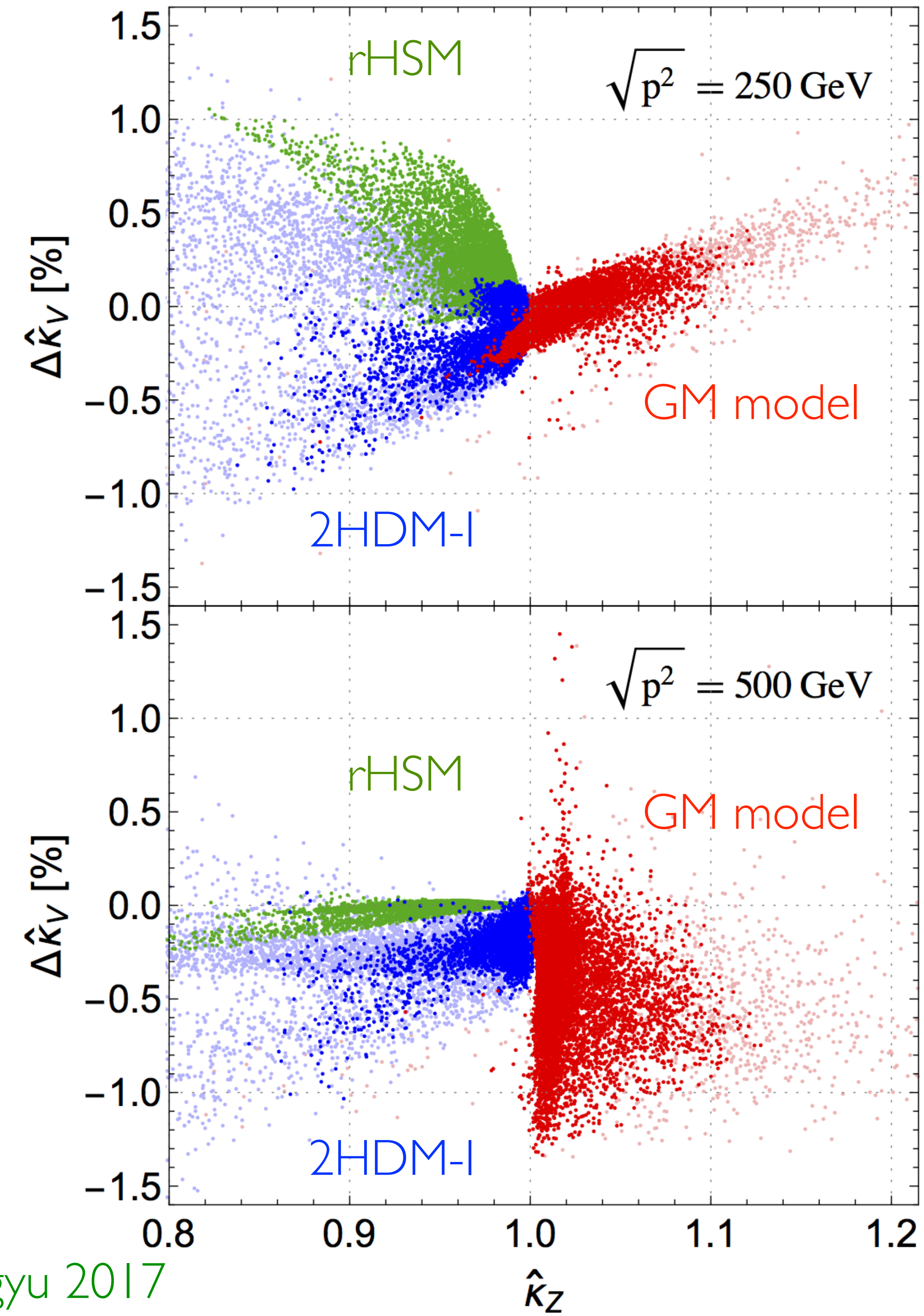
- Radiative corrections in SM:

$$\frac{g_{hVV}^{1-{\rm loop}}}{g_{hVV}^{\rm tree}} \simeq \begin{cases} -1.2 \quad (+1.0)\ \% \quad (hZZ)\ , \\ +0.4 \quad (+1.3)\ \% \quad (hWW)\ , \end{cases} \qquad \text{for } \sqrt{p^2} = 250\ (500)\ \text{GeV}$$

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

MORE EXOTIC MODELS

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

15 scenarios allowed

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)

n = 4 GM model w/o custodial symmetry ➠ (3/2,3/2) ≥ (3/2,1/2)

all involve a representation with T = Y that gives a negative contribution to ρ

septet at most

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

11 cases with r > 1
2 cases with r = 1
2 cases with r < 1

Neutral Higgs Mixing

- CP-even 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:

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

common part

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

dependent only on hypercharges

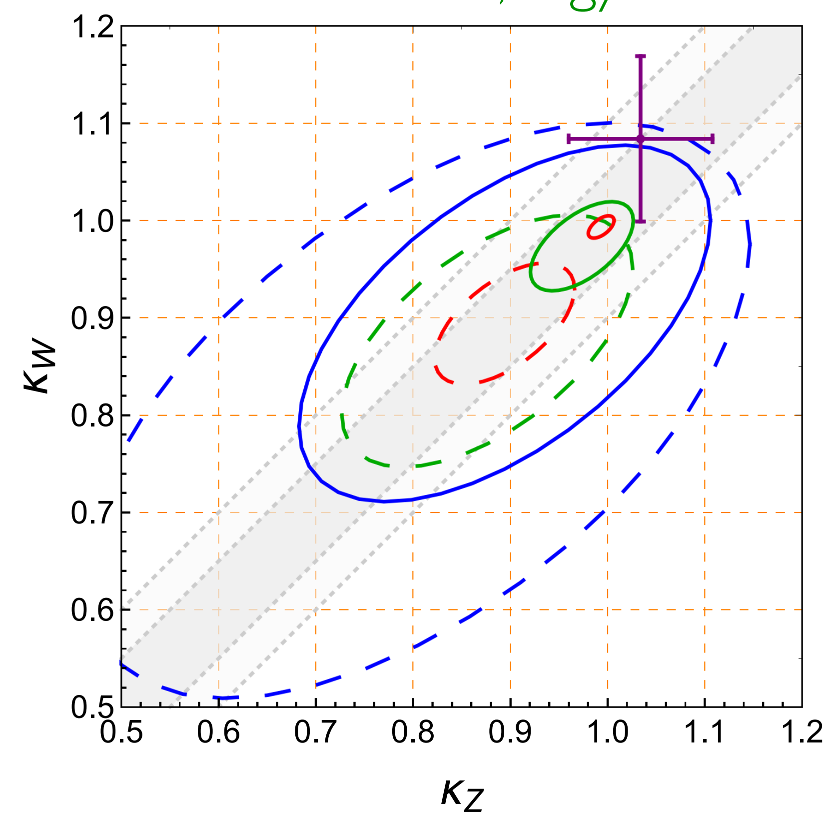
$$R' \equiv \sqrt{1 - R_{11}^2}$$

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

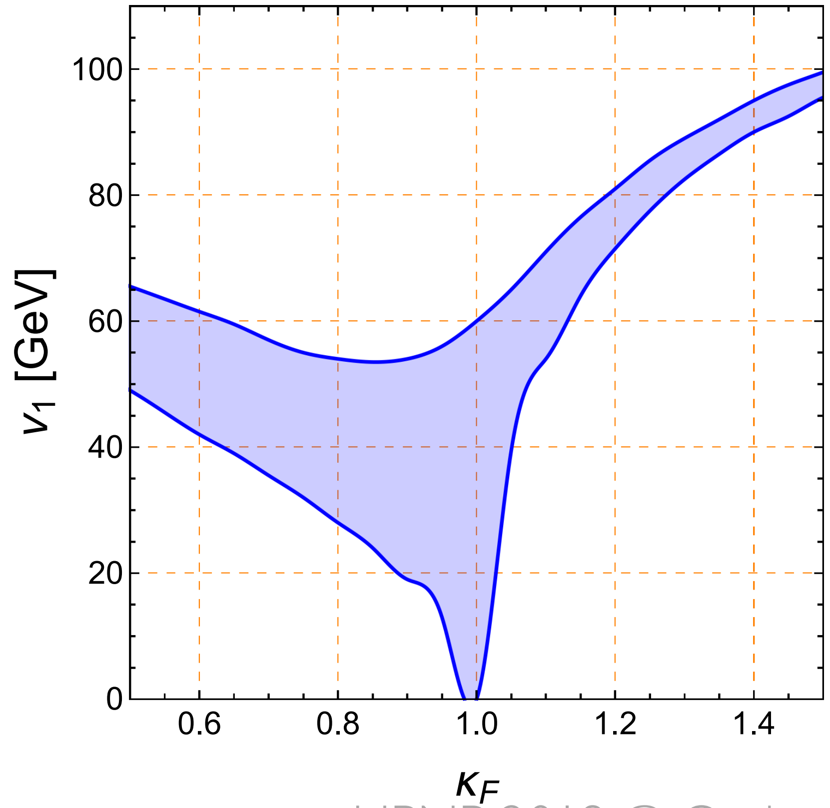
First Scenario

- Correlation plot for κ_F = 0.9 (dashed) and 1.0 (solid) with v_1 = 10 (red), 20 (green) and 40 (blue) GeV, by scanning mixing angle θ.
- The dark (light) gray band indicates $|\kappa_Z - \kappa_W| \leq 0.05$ (0.10).
- The purple cross marks current data at 1σ.

CWC, Yagyu 2018



- Blue region allowed by current data of $\kappa_{W,Z}$ at 1σ level.
- Except for SM-like limit, there generally exist upper and lower bounds on v_Δ.
  ➟ importance about knowledge of κ_F



DETERMINATION OF K_W/K_Z

κ_W/κ_Z

- The ratio

$$\lambda_{WZ} \equiv \frac{\kappa_W}{\kappa_Z}$$

  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, data show that

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

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

  ➠ a two-fold ambiguity in such measurements
- With 3/ab, the HL-LHC is anticipated to achieve

$$|\delta\kappa_W/\kappa_W| \leq 5\% \ , \ |\delta\kappa_Z/\kappa_Z| \leq 4\% \ \Rightarrow \ |\delta\lambda_{WZ}/\lambda_{WZ}| \leq 6.4\%$$

  assuming that the central values remain SM-like.
  ➠ no good way to resolve sign ambiguity

Solving the Ambiguity

- How can we experimentally determine this ratio, especially its sign?
- It can be measured in $H \to ZZ^* \to 4\ell$ due to the interference between tree and one-loop amplitudes, which are proportional to the HZZ and HWW couplings, respectively.

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

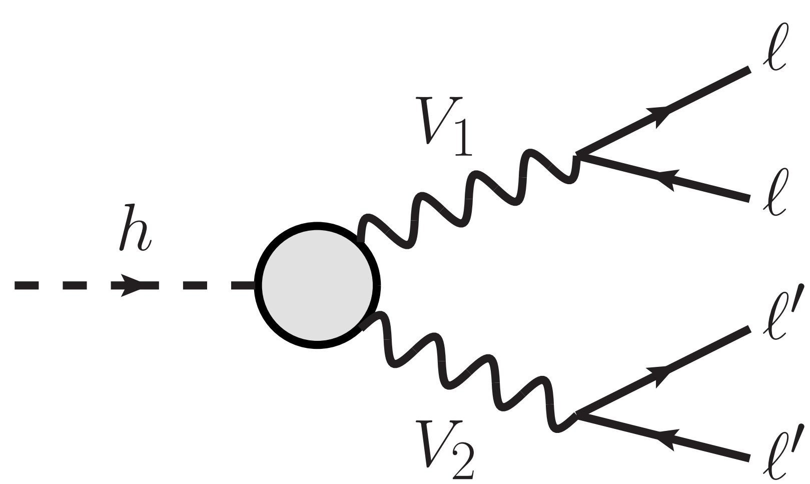
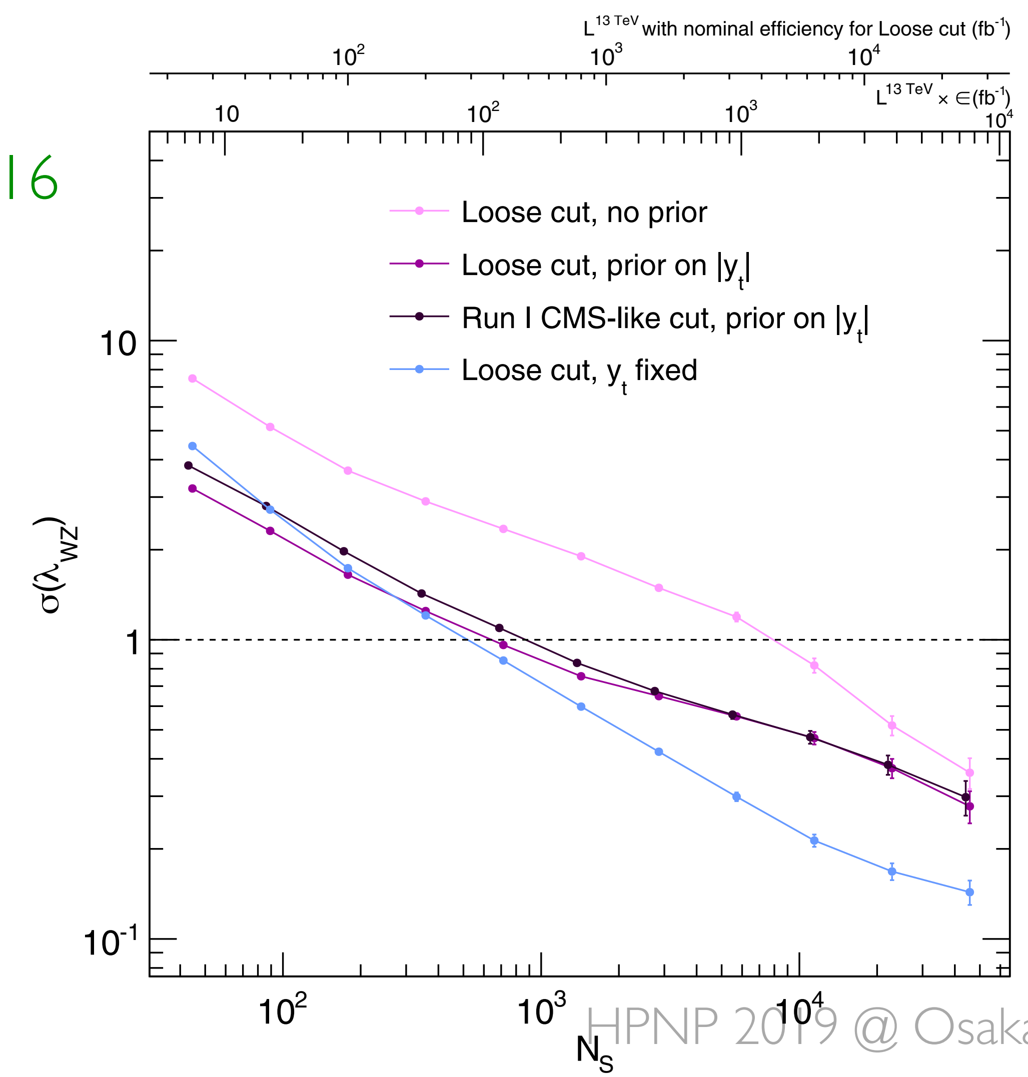


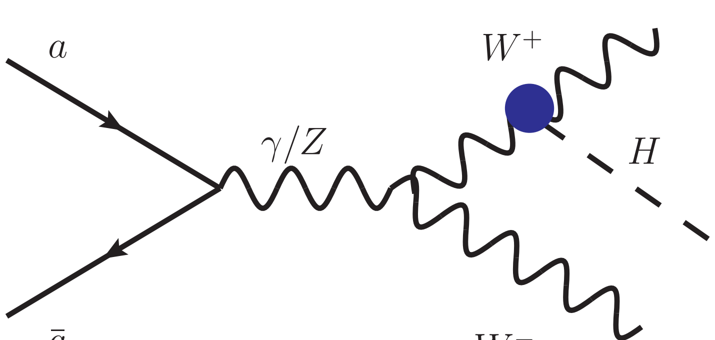
FIG. 1. Schematic representation of the hVV contributions to the $h \to 4\ell$ amplitude where $V_{1,2} = Z, \gamma$ and $\ell, \ell' = e, \mu$.



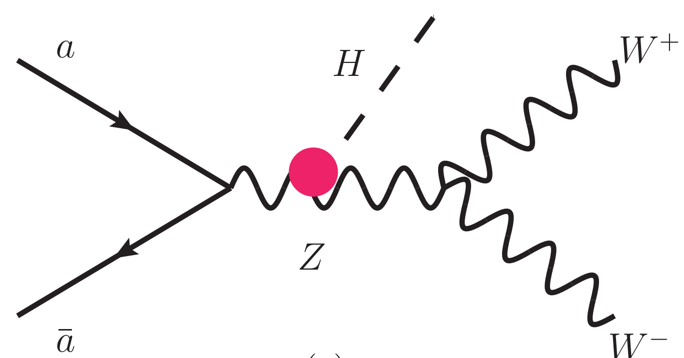
Solving the Ambiguity

- How can we experimentally determine this ratio, especially its sign?
- We propose to consider the $e^+e^- \to W^+W^-H$ process, where a desirable interference occurs among the tree-level amplitudes and allows us to experimentally fix λ_{WZ}.

CWC, He, Li 2018

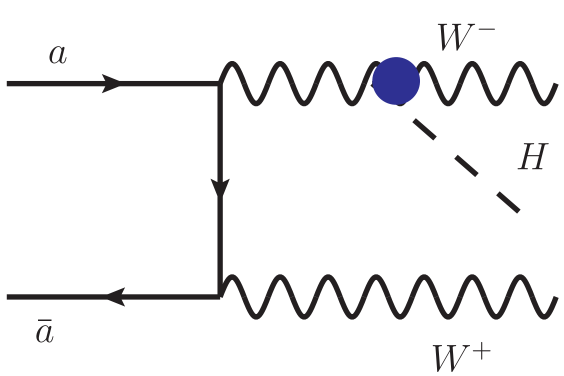


(a)



(c)

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



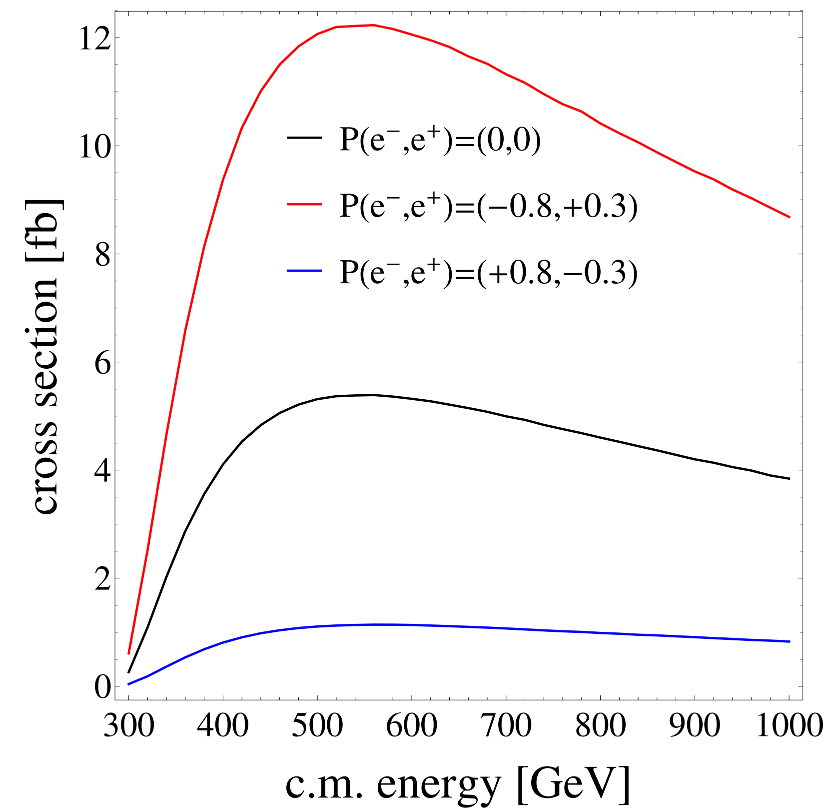
(b)

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

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 generally changes 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]

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

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

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

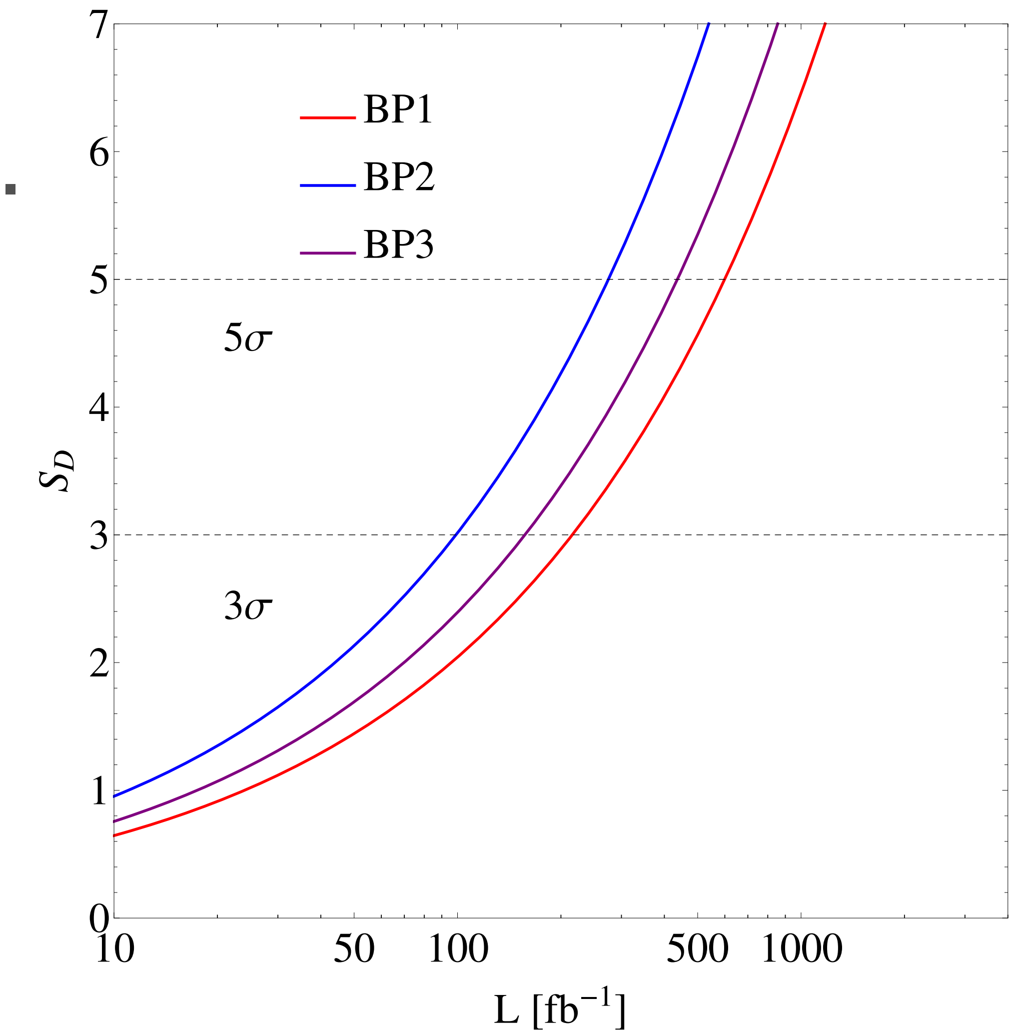
Remarks

- Our proposal is a simple counting measurement.
- The interference term can certainly result in noticeable effects on differential distributions, such as that of the rapidity of the charged lepton and that of the azimuthal angle difference between the charged lepton and the leading-p_T light jet.
- These distributions generally require more statistics in order to reach the same sensitivity for λ_{WZ} as proposed here.

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 $H \to b\bar{b}$.
- 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

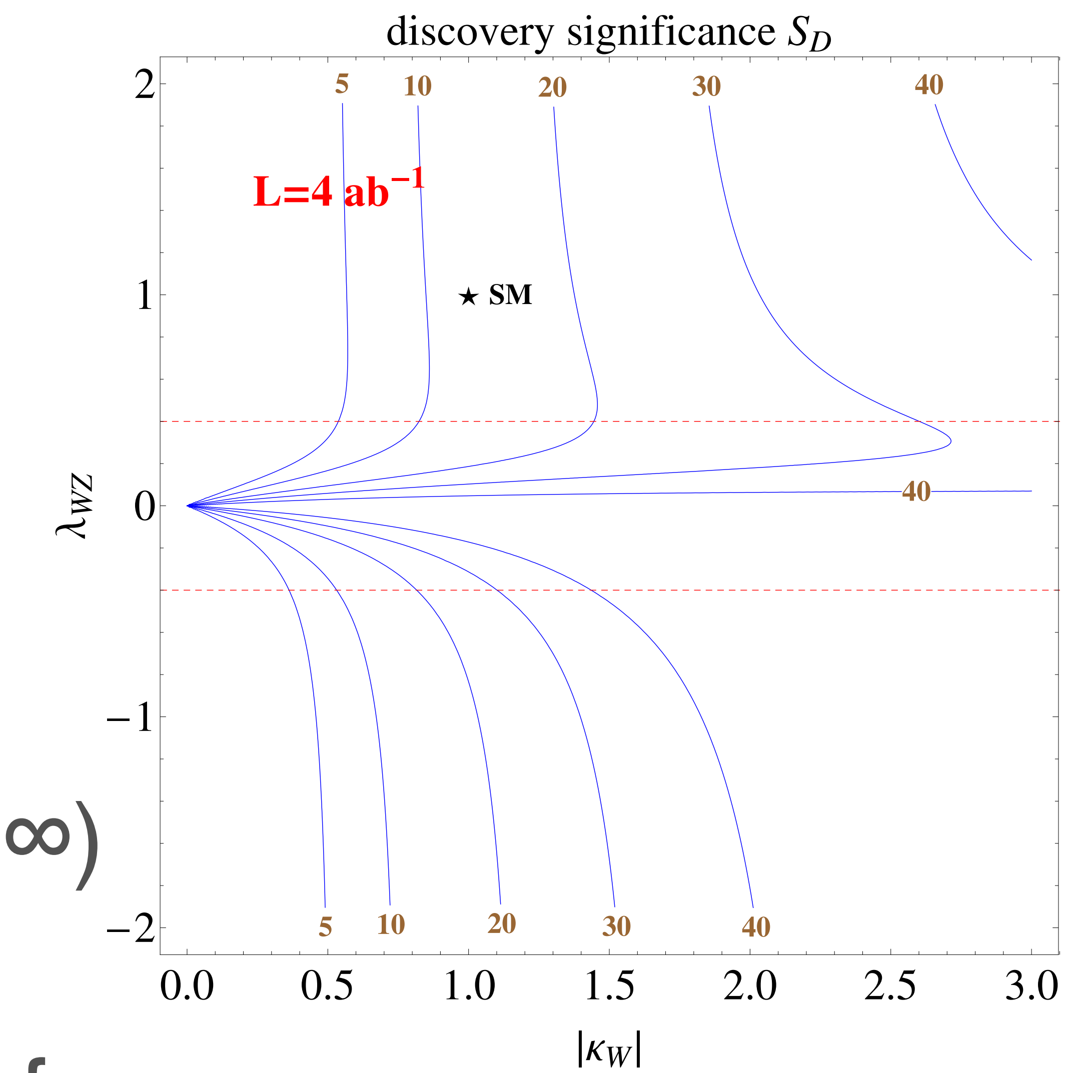


signal significance as a function of L

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

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. ($\lambda_{WZ} \to 0$ ➠ $\kappa_Z \to \infty$)
- 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.



Summary

- Knowledge of $\kappa_{W,Z}$ is crucial for our understanding of EWSB and the Higgs sector.
- Current data show tantalizing hints of "non-standard" $\kappa_{W,Z}$:
  (1) either one could be slightly 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 to determine magnitudes and relative sign of $\kappa_{W,Z}$ through interference in the $e^+e^- \to HW^+W^-$ process at ILC-500, along with LHC inputs.