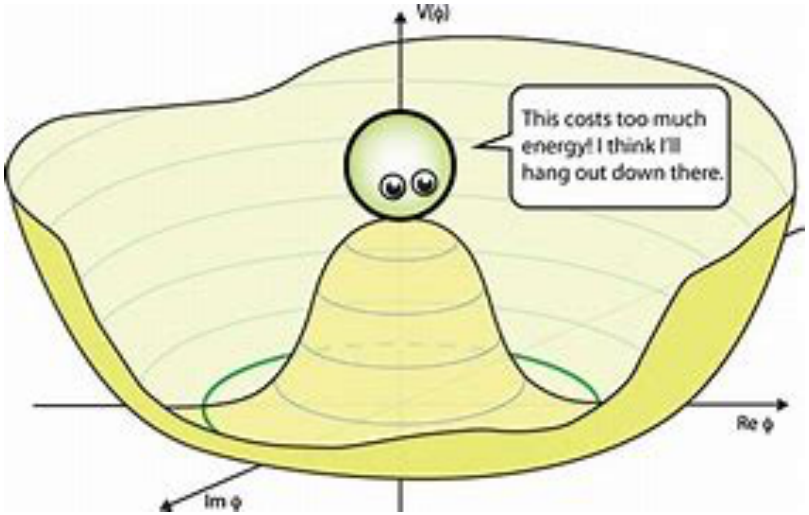
Probing the electroweak symmetry breaking with Higgs production at the LHC

Bin Yan
Institute of High Energy Physics

MBI 2022
Aug 22-25, 2022

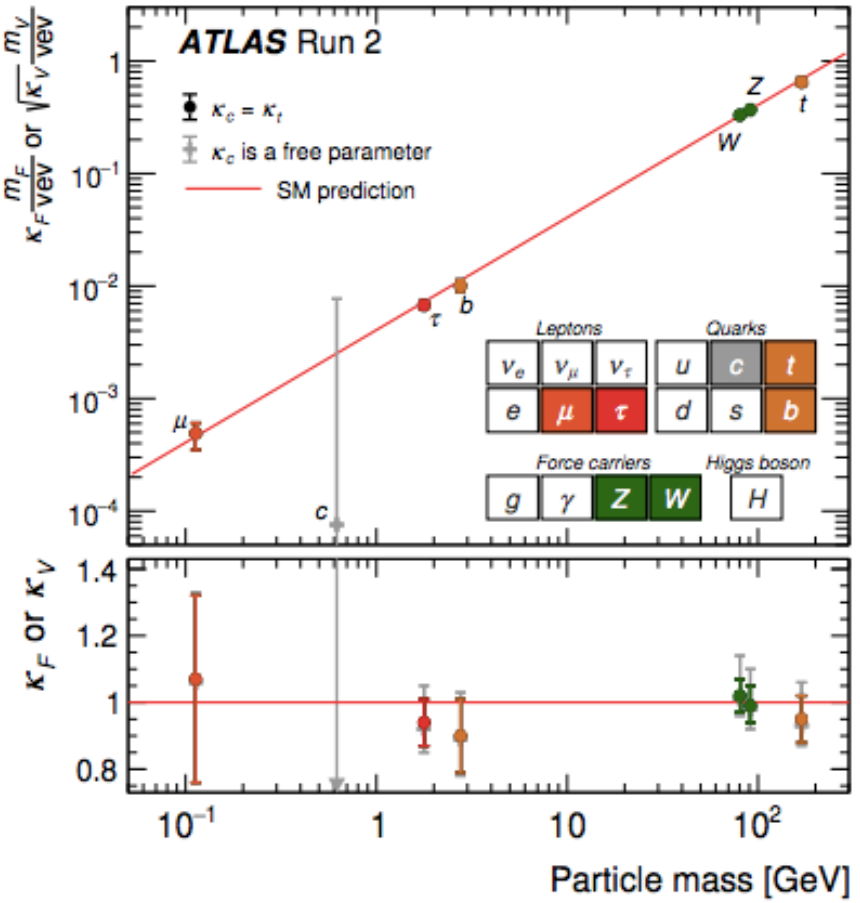
K. P. Xie and Bin Yan, PLB820(2021)136515

Higgs couplings and EWSB

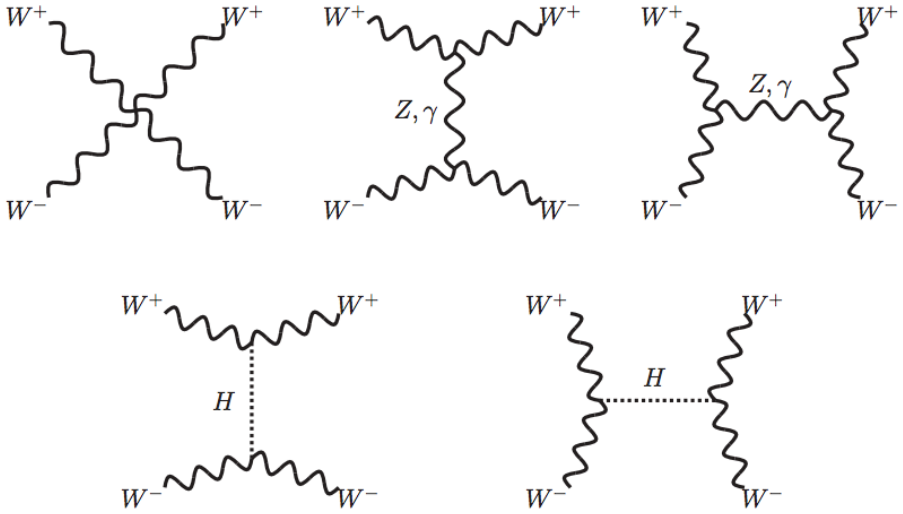


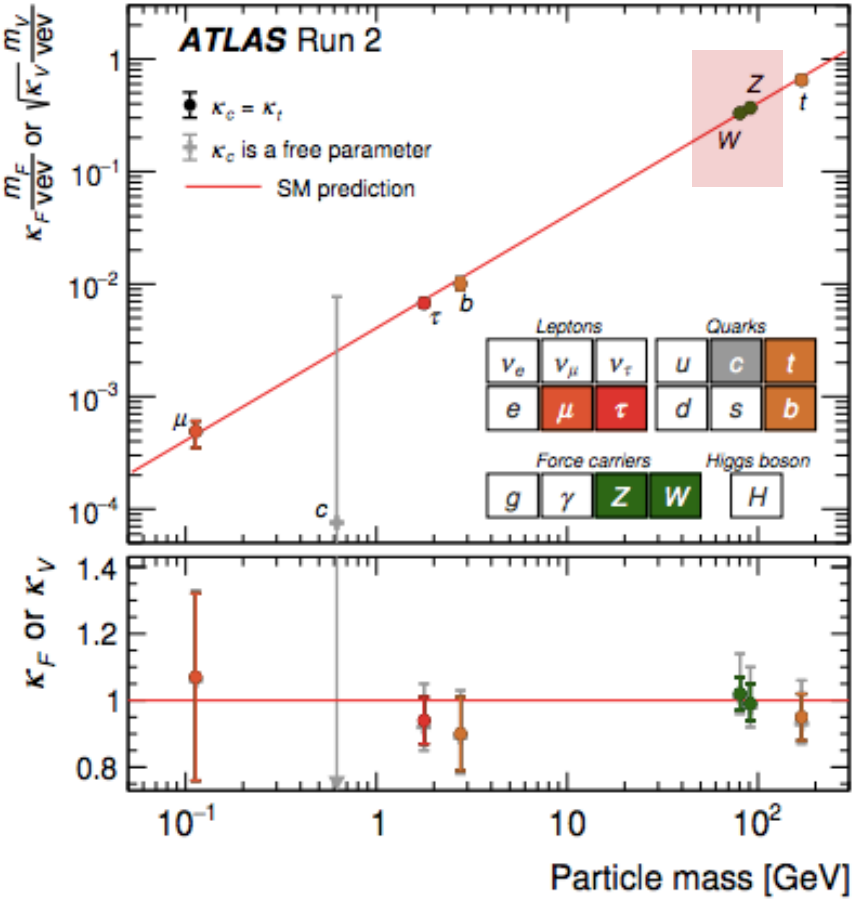
Higgs mechanism

All fundamental particles get their mass from Higgs boson vev



Higgs couplings and EWSB





HVV couplings play the key role to probe the EWSB

Higgs couplings and EWSB

$$\mathcal{L}_{hVV} = \kappa_W g^{\rm SM}_{hWW} h W^+_\mu W^{-\mu} + \frac{\kappa_Z}{2} g^{\rm SM}_{hZZ} h Z_\mu Z^\mu,$$

$$g^{\rm SM}_{hVV} = 2m^2_V/v \qquad\qquad \lambda_{WZ} \equiv \frac{\kappa_W}{\kappa_Z}$$

The other operators will be induced from the loop level

C. Arzt, M.B. Einhorn and J. Wudka, NPB 433,41(1995)

e.g. $H^+ H B_{\mu\nu} B^{\mu\nu}, (D^\mu H)^+ (D^\nu) B_{\mu\nu}, (D^\mu H)^+ \sigma^i (D^\nu H) W^I_{\mu\nu}$

To verify the EWSB, we need to determine:

(1)The magnitude of the Higgs couplings

(2) The relative sign between hWW and hZZ couplings

Higgs couplings and New Physics

$$\mathcal{L}_{hVV} = \kappa_W g^{\rm SM}_{hWW} h W^+_\mu W^{-\mu} + \frac{\kappa_Z}{2} g^{\rm SM}_{hZZ} h Z_\mu Z^\mu,$$

(1) The magnitude of Higgs couplings @NP

For example:

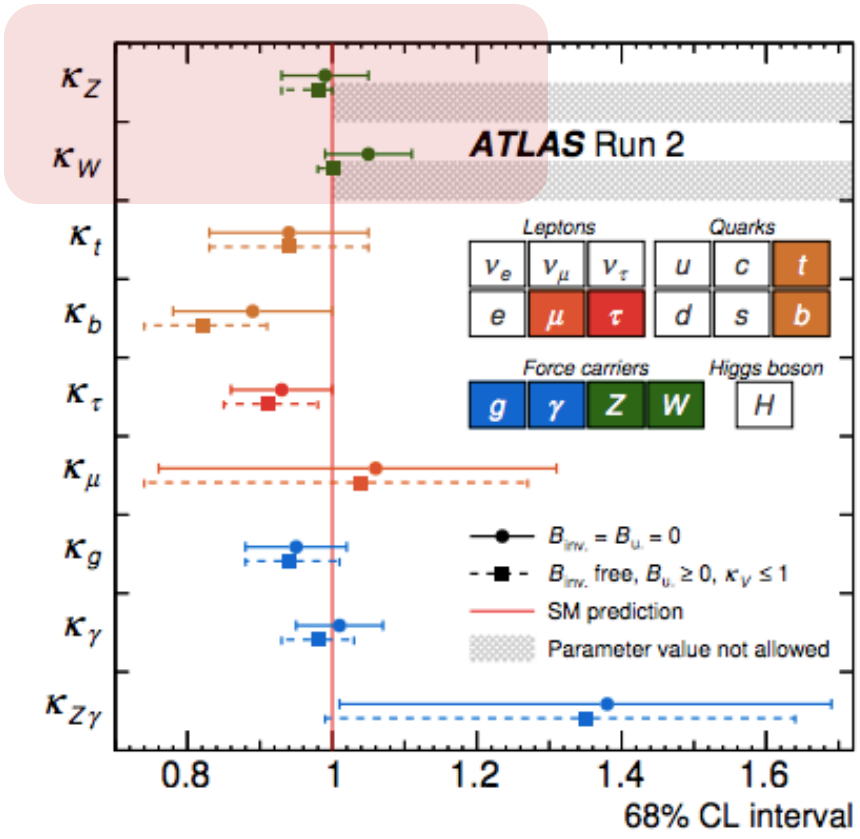
Composite Higgs models

$$\kappa_W = \kappa_Z = \sqrt{1-\xi}, \quad \xi = \frac{v^2}{2f^2}$$

e.g. I. Low, 1412.2145,1412.2146
Q. H. Cao, L. X. Xu, Bin Yan and S. H. Zhu, PLB789(2019)233-237

Non-compact groups $\xi \to -\xi$

R. Alonso, E. E. Jenkins, A. V. Manohar, PLB756(2016) 358-364



Higgs couplings and New Physics

$$\mathcal{L}_{hVV} = \kappa_W g^{\rm SM}_{hWW} h W^+_\mu W^{-\mu} + \frac{\kappa_Z}{2} g^{\rm SM}_{hZZ} h Z_\mu Z^\mu,$$

(1) The magnitude of Higgs couplings @NP

For example:

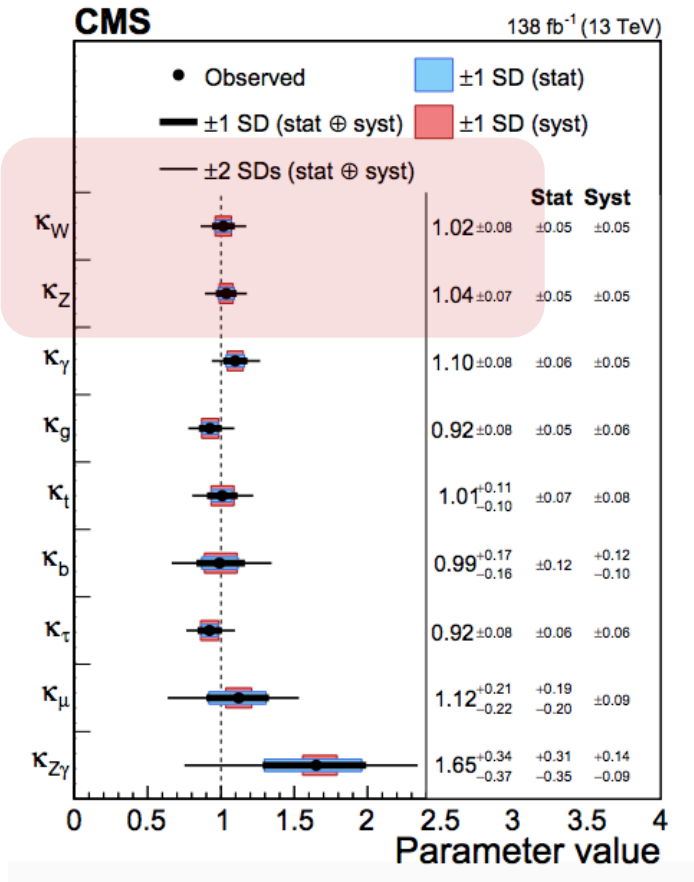
Composite Higgs models

$$\kappa_W = \kappa_Z = \sqrt{1-\xi}, \quad \xi = \frac{v^2}{2f^2}$$

e.g. I. Low, 1412.2145,1412.2146
Q. H. Cao, L. X. Xu, Bin Yan and S. H. Zhu, PLB789(2019)233-237

Non-compact groups $\xi \to -\xi$

R. Alonso, E. E. Jenkins, A. V. Manohar, PLB756(2016) 358-364

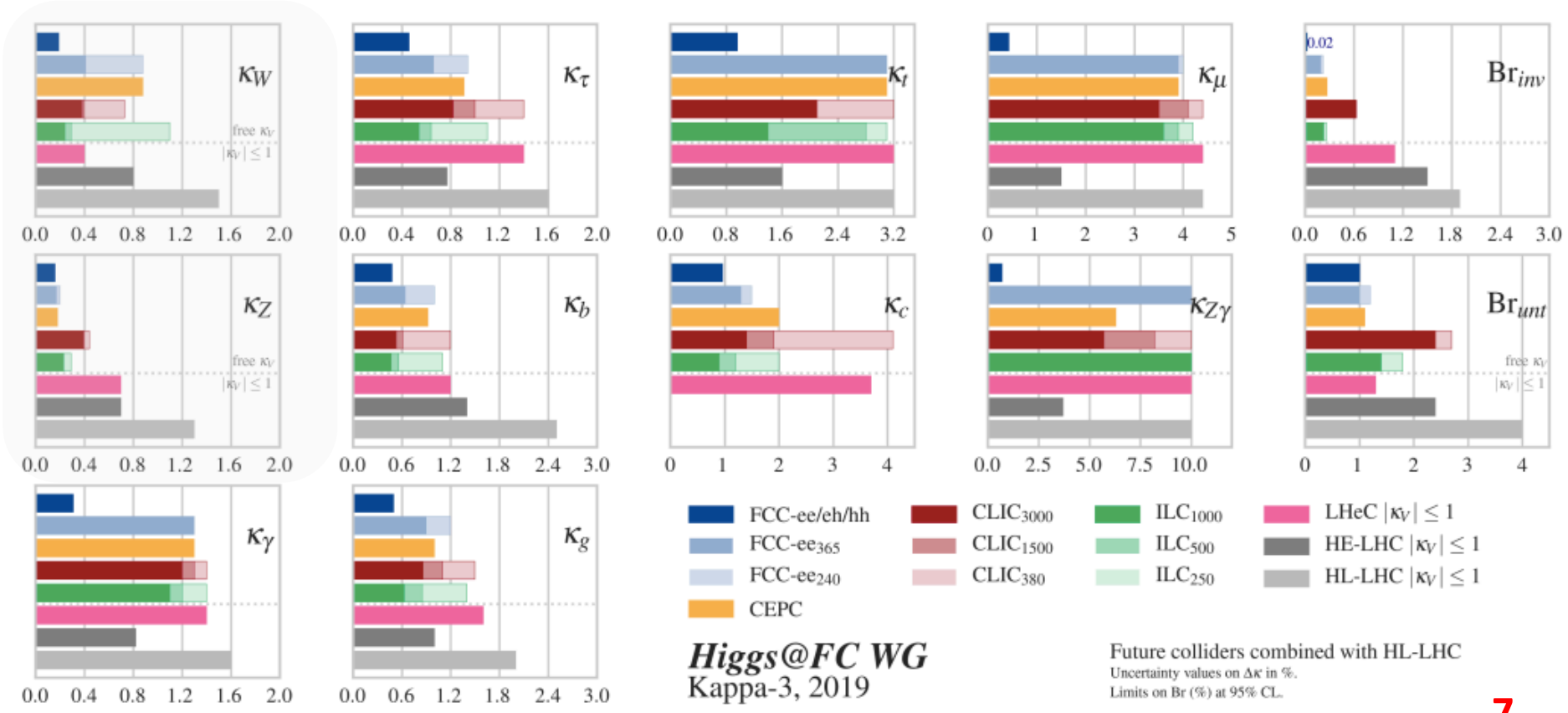


Higgs couplings and New Physics

$$\mathcal{L}_{hVV} = \kappa_W g^{\rm SM}_{hWW} h W^+_\mu W^{-\mu} + \frac{\kappa_Z}{2} g^{\rm SM}_{hZZ} h Z_\mu Z^\mu,$$

(1) The magnitude of Higgs couplings @NP

2206.08326



Higgs couplings and New Physics

$$\mathcal{L}_{hVV} = \kappa_W g^{\rm SM}_{hWW} h W^+_\mu W^{-\mu} + \frac{\kappa_Z}{2} g^{\rm SM}_{hZZ} h Z_\mu Z^\mu,$$

(2) The negative relative sign of Higgs couplings @NP

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

I. Low, J. Lykken, JHEP10(2010)053

It depends on the custodial representation of Higgs.

$\lambda_{WZ} < 0$ e.g. fiveplet in Georgi-Machacek model

$\lambda_{WZ} = -1, \rho = 1$ C.H.d. Lima, D. Stolarski, Y. Wu, PRD 105(2022)3,035019

Directly probing the sign is very important for testing EWSB

So…

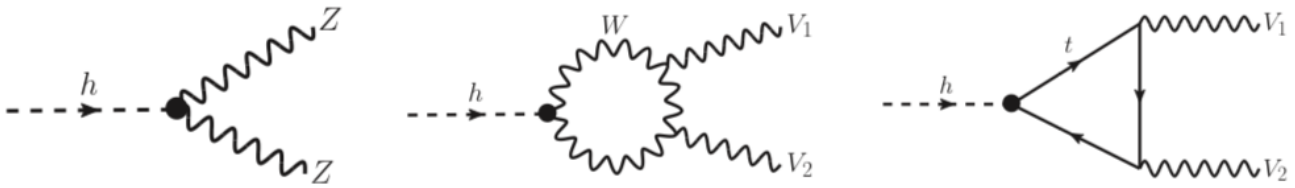
How to fix the relative sign between hWW and hZZ couplings

EWSB@LHC

Y. Chen, M. Spiropulu, D. Stolarski and R. V. Morales, PRL117(2016)24,241801

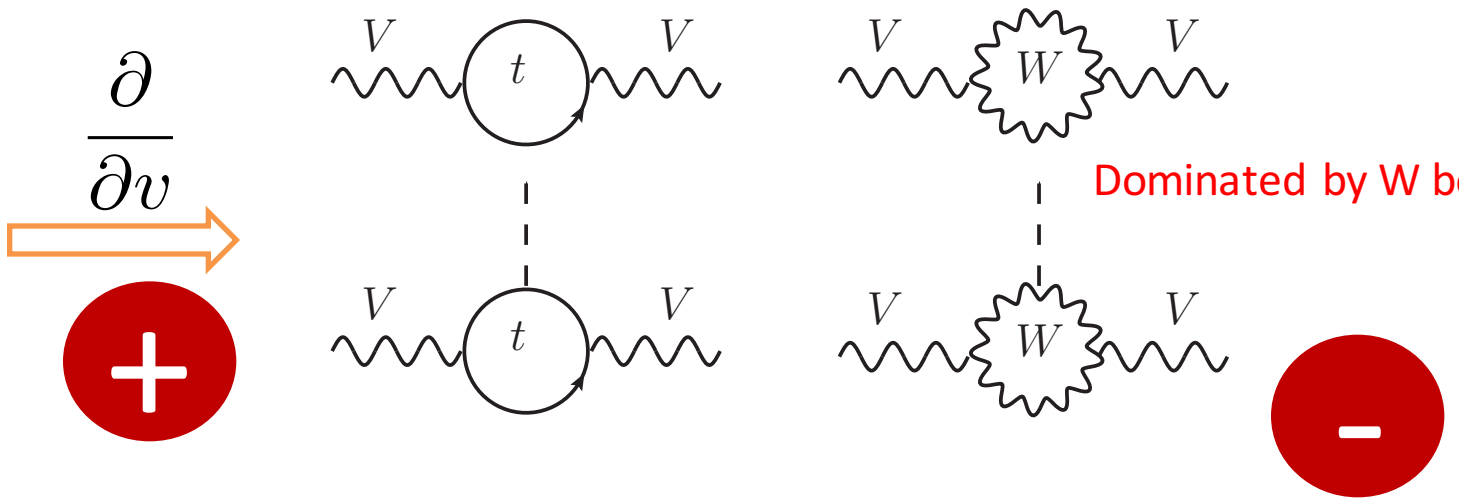
The interference between tree and loop level processes

$h \to 4\ell$



Low Energy Theorem: Dawson and Haber (1989)

$$\frac{\partial}{\partial v}$$



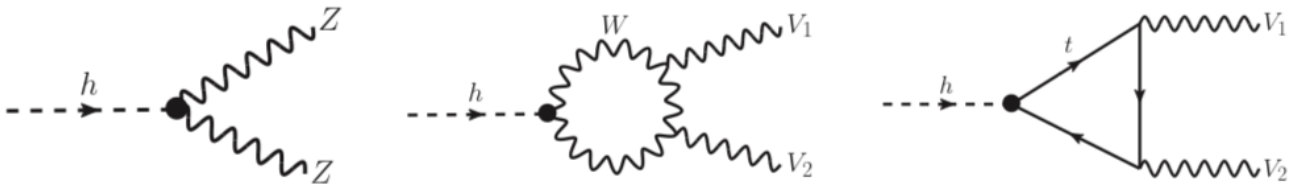
Dominated by W boson loop

EWSB@LHC

Y. Chen, M. Spiropulu, D. Stolarski and R. V. Morales, PRL117(2016)24,241801

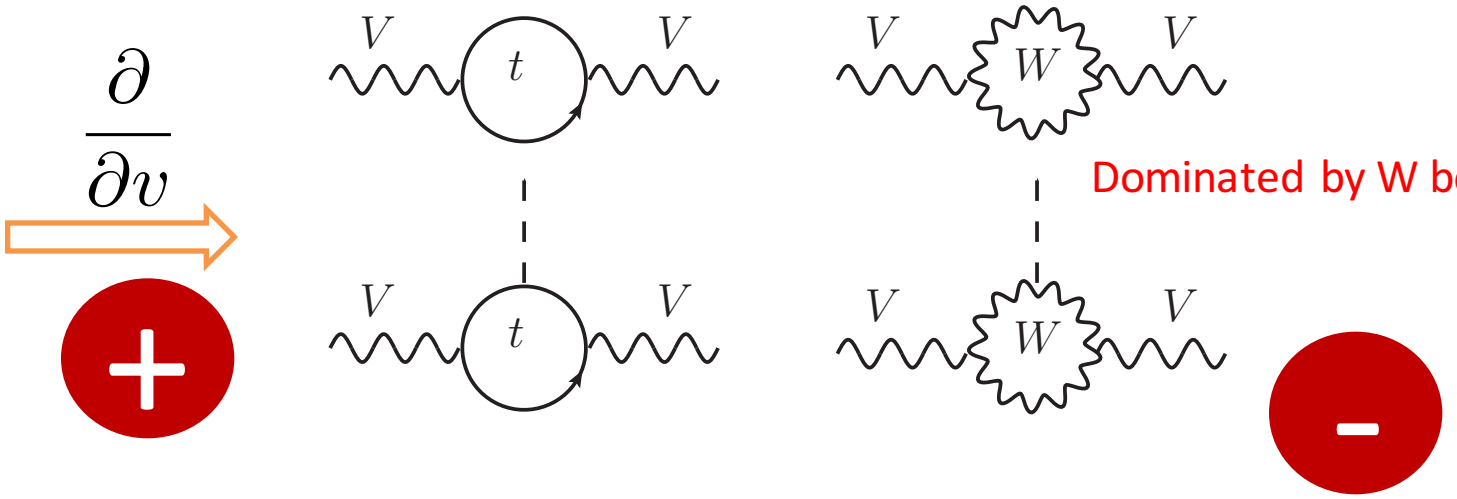
The interference between tree and loop level processes

$h \to 4\ell$



This process is sensitive to the sign $\lambda_{WZ} \equiv \frac{\kappa_W}{\kappa_Z}$

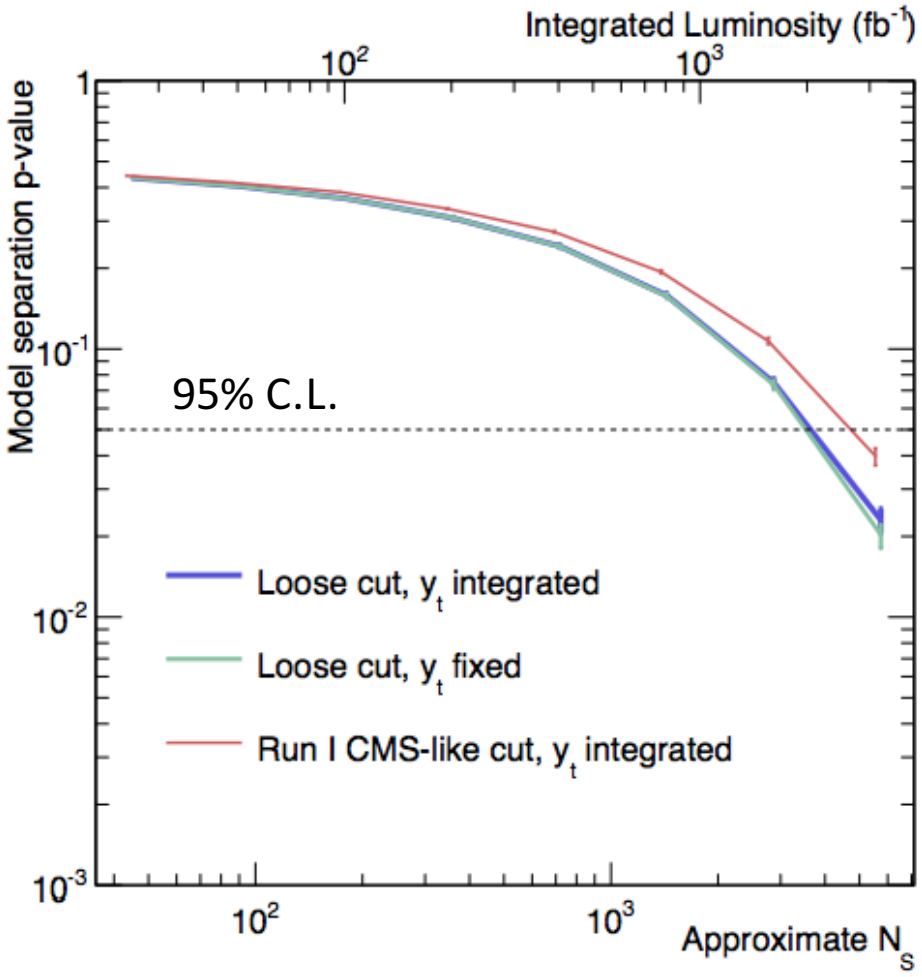
$\frac{\partial}{\partial v}$



Dominated by W boson loop

EWSB@LHC

Y. Chen, M. Spiropulu, D. Stolarski and R. V. Morales, PRL117(2016)24,241801



The probability of mistaking a SM Higgs for a custodial fiveplet

The fiveplet has been excluded by the recent LHC data

$$\text{fiveplet} : \lambda_{WZ} = -\frac{1}{2}$$

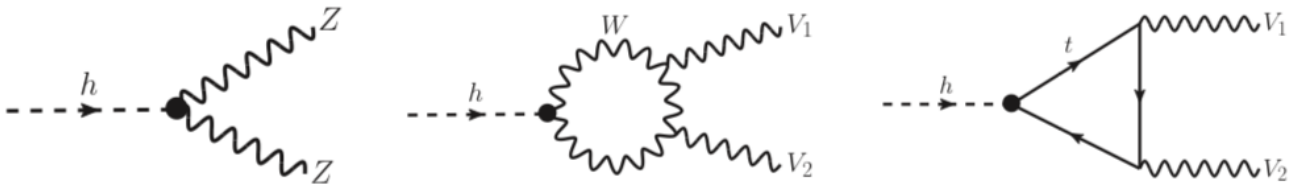
Nature 607 (2022) 7917, 52-59

EWSB@LHC

Y. Chen, M. Spiropulu, D. Stolarski and R. V. Morales, PRL117(2016)24,241801

The interference between tree and loop level processes

$h \to 4\ell$



How about the other possible new physics effects? Loophole?

Loop level operators:

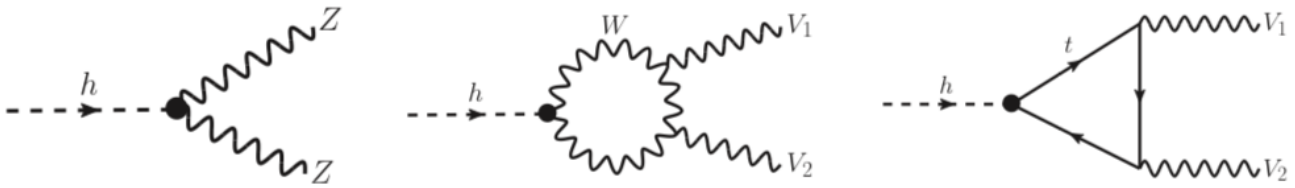
$$HZ_{\mu\nu}Z^{\mu\nu}, HZ_{\mu\nu}F^{\mu\nu}, HF_{\mu\nu}F^{\mu\nu}?$$

EWSB@LHC

Y. Chen, M. Spiropulu, D. Stolarski and R. V. Morales, PRL117(2016)24,241801

The interference between tree and loop level processes

$h \to 4\ell$



How about the other possible new physics effects? Loophole?

Loop level operators:

$$HZ_{\mu\nu}Z^{\mu\nu}, HZ_{\mu\nu}F^{\mu\nu}, HF_{\mu\nu}F^{\mu\nu}?$$

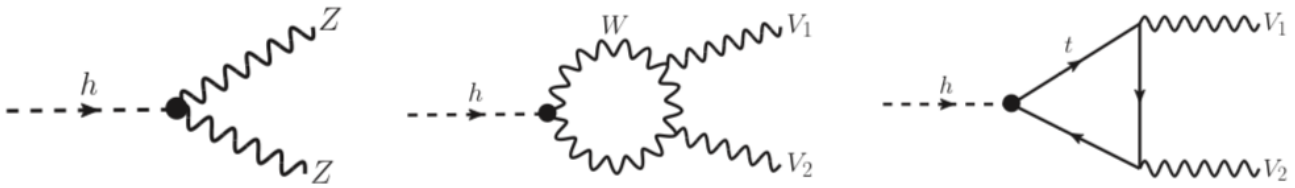
Suppressed by Z boson mass

EWSB@LHC

Y. Chen, M. Spiropulu, D. Stolarski and R. V. Morales, PRL117(2016)24,241801

The interference between tree and loop level processes

$h \to 4\ell$



How about the other possible new physics effects? Loophole?

Loop level operators:

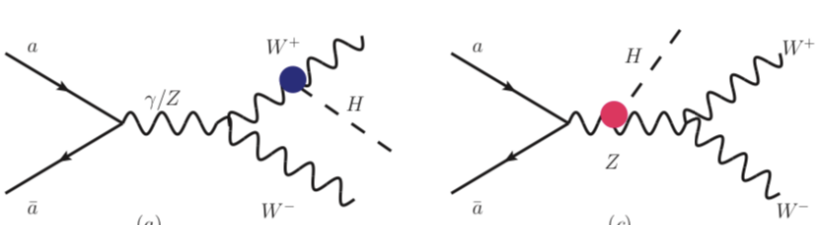
$$HZ_{\mu\nu}Z^{\mu\nu}, HZ_{\mu\nu}F^{\mu\nu}, HF_{\mu\nu}F^{\mu\nu}?$$

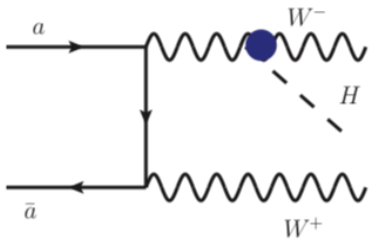
It is also more sensitive to the hZZ coupling, while not for hWW coupling

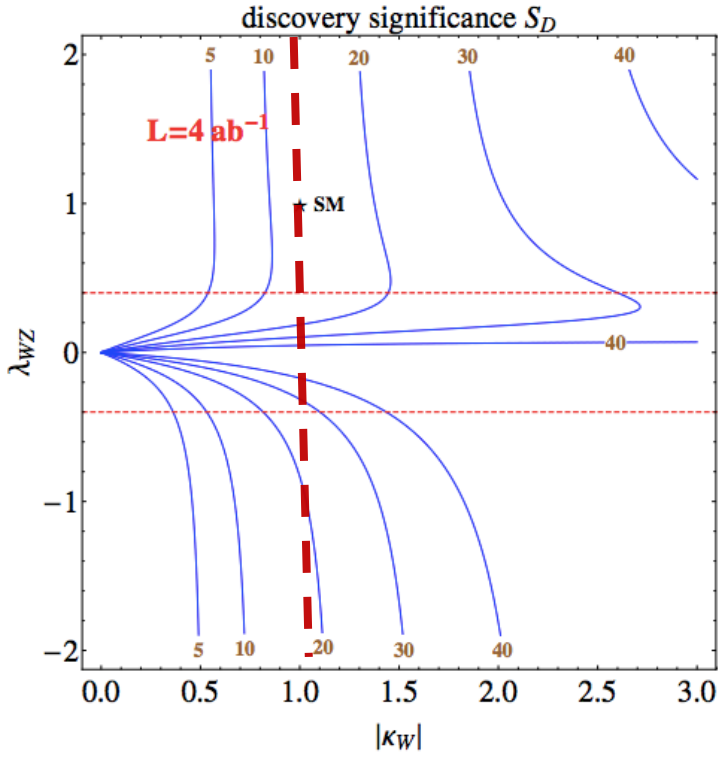
EWSB@ lepton colliders

$e^+e^- \to W^+W^-H$

C.W Chiang, X. G. He and G. Li, JHEP08(2018) 126







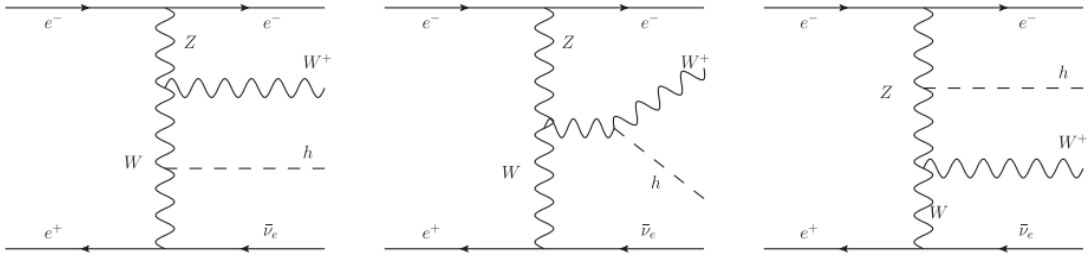
The destructive interference effects

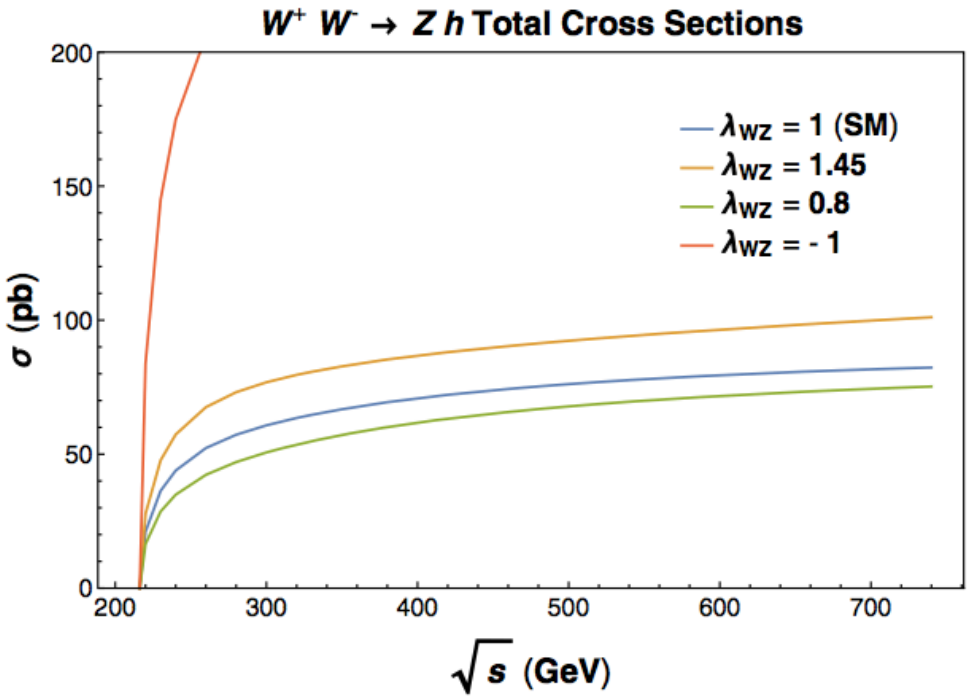
500 GeV @ ILC

EWSB@ lepton colliders

$e^+e^- \to \nu_e\bar{\nu}_e ZH/\nu_e eWH$

D. Stolarski and Y. Wu, PRD102(2020)3,033006



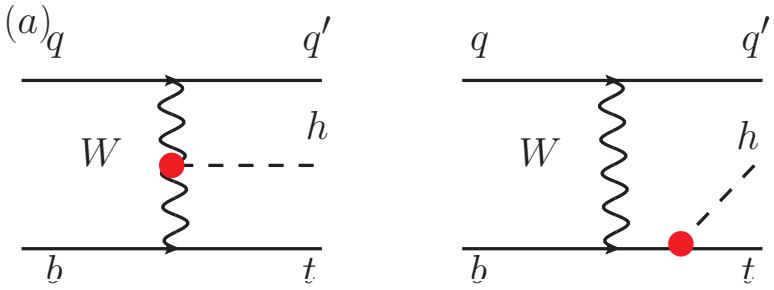


The cross section is sensitive to the sign: from the unitarity of the VV scattering

th and Zh production

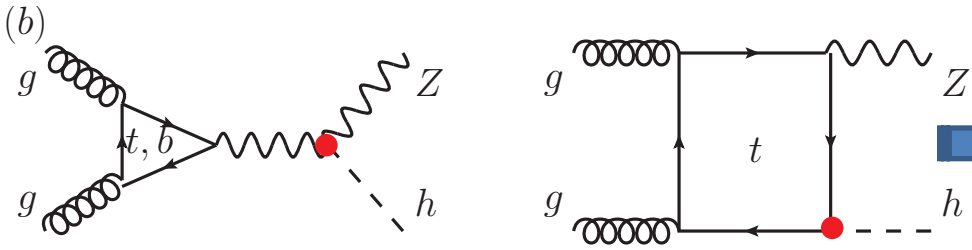
K. P. Xie and Bin Yan, PLB820(2021)136515

M. Farina et al, 1211,373
A. Kobakhidze et al, 1406.1961
S.D.Rindani et al, 1605.03806
….



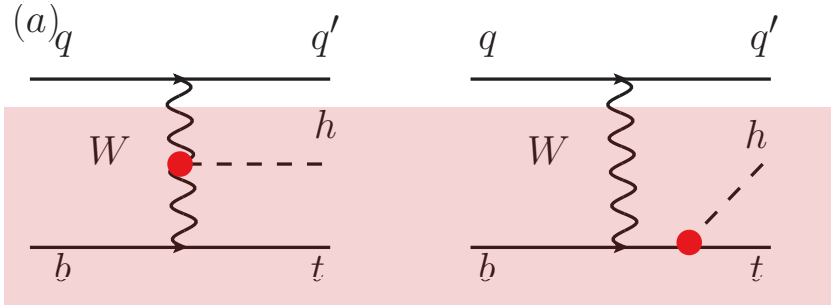
Cross section is sensitive to the relative sign between htt and hWW

Top quark Yukawa coupling as a bridge



Cross section is sensitive to the relative sign between htt and hZZ

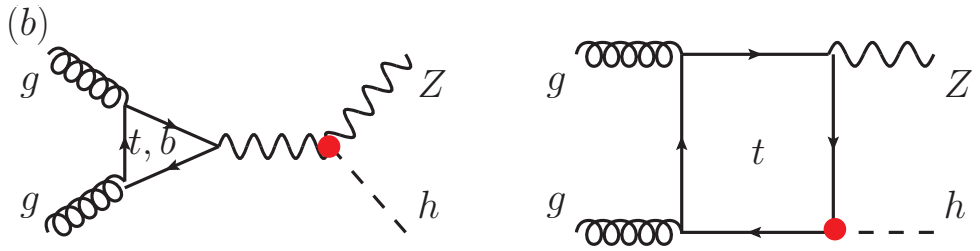
High Energy behavior



relative sign between htt and hWW

$$bW^{\mu} \to ht$$

$$M \sim \bar{u}(t)\left[m_t(\kappa_t - \kappa_W) + \left(\frac{2m_W^2}{u}\kappa_W + \frac{m_t^2}{s}\kappa_t\right)\not{p}_W\right]P_L u(b)$$



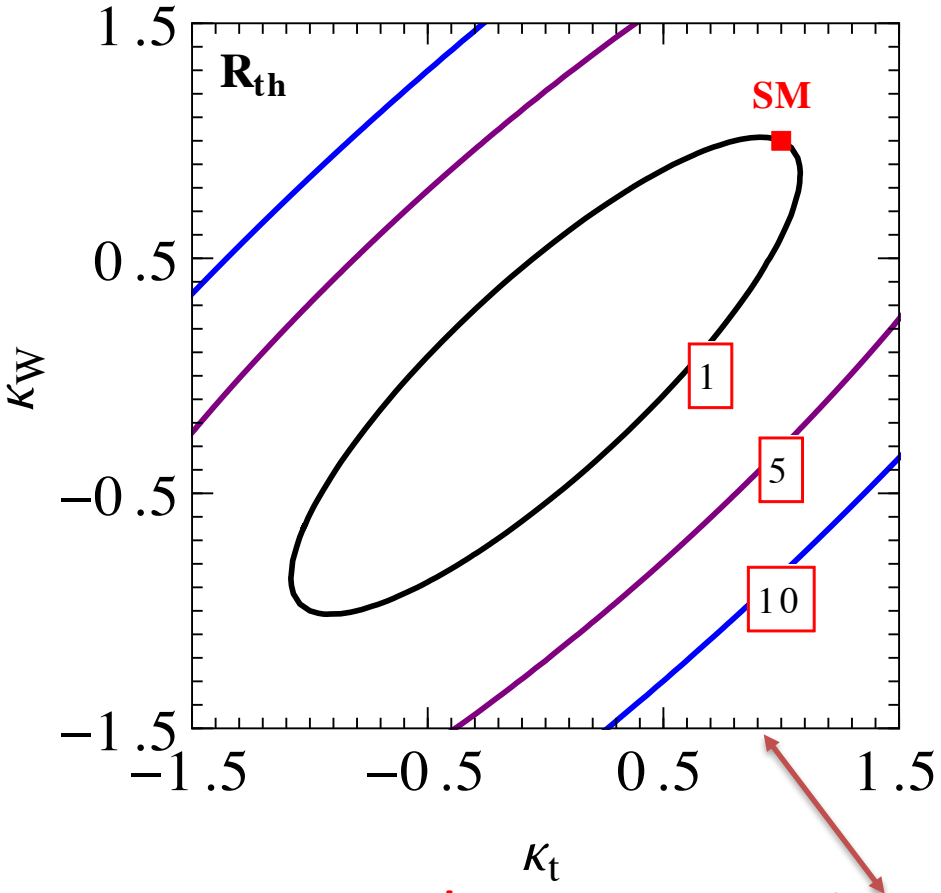
relative sign between htt and hZZ

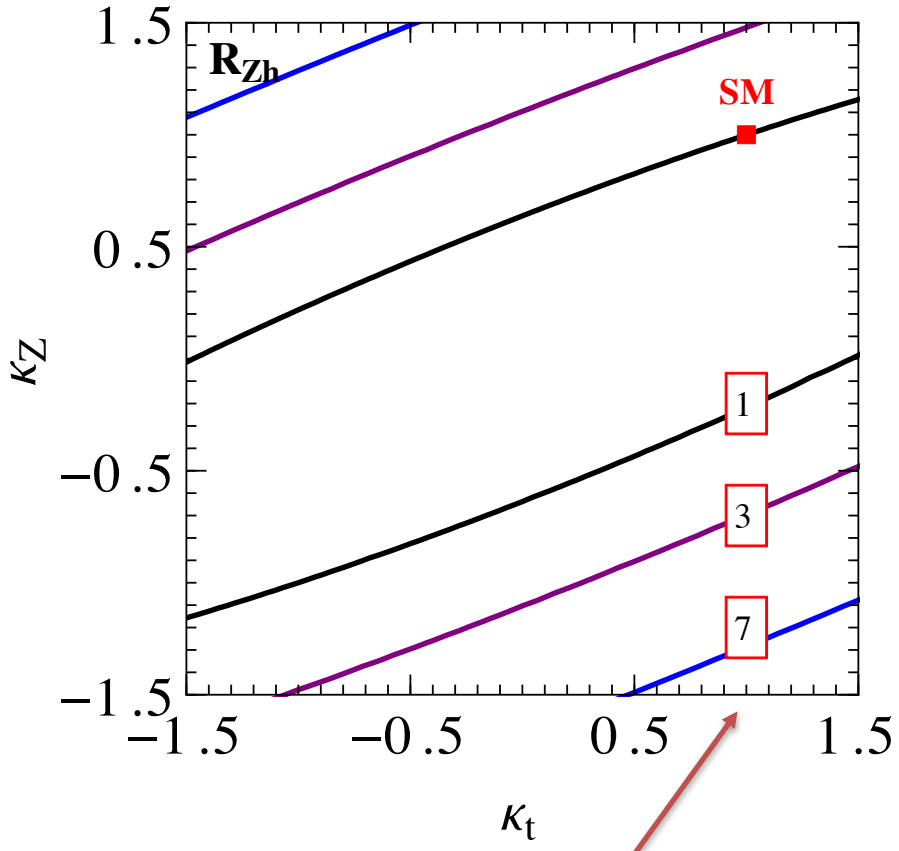
$$M_{\pm,\pm,0} \sim \frac{m_t^2}{m_Z^2}(\kappa_Z - \kappa_t)\log^2\left(-\frac{s}{m_t^2}\right)$$

Cross sections@ 13 TeV LHC

$$R_{th} = \frac{\sigma(pp \to th)}{\sigma^{\rm SM}(pp \to th)}$$

$$R_{Zh} = \frac{\sigma(gg \to Zh)}{\sigma^{\rm SM}(gg \to Zh)}$$

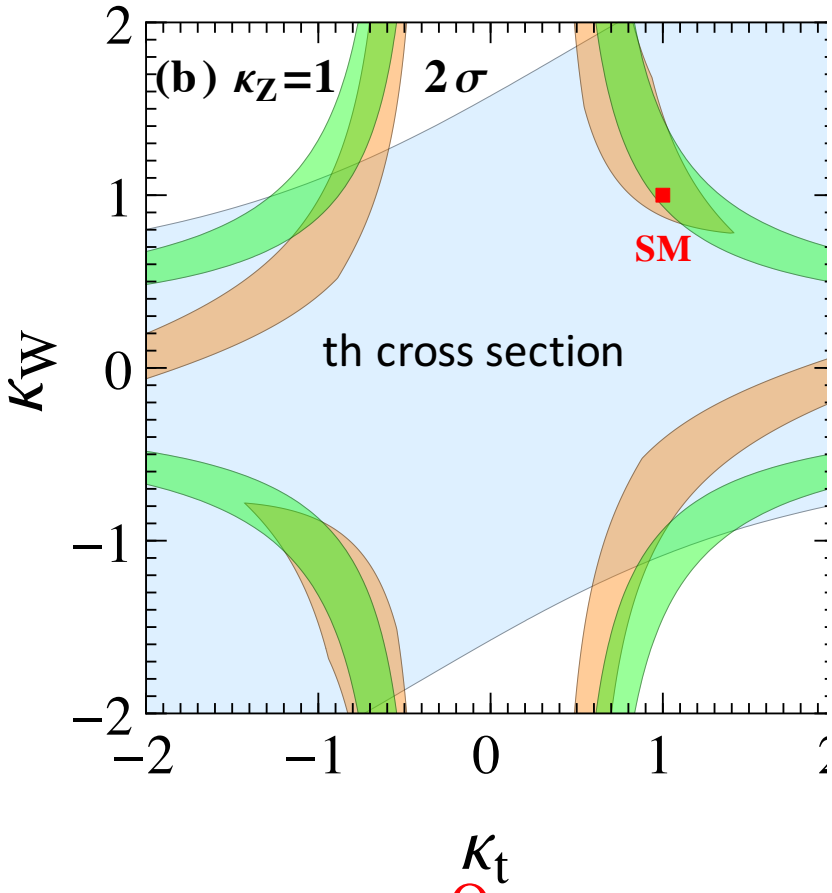




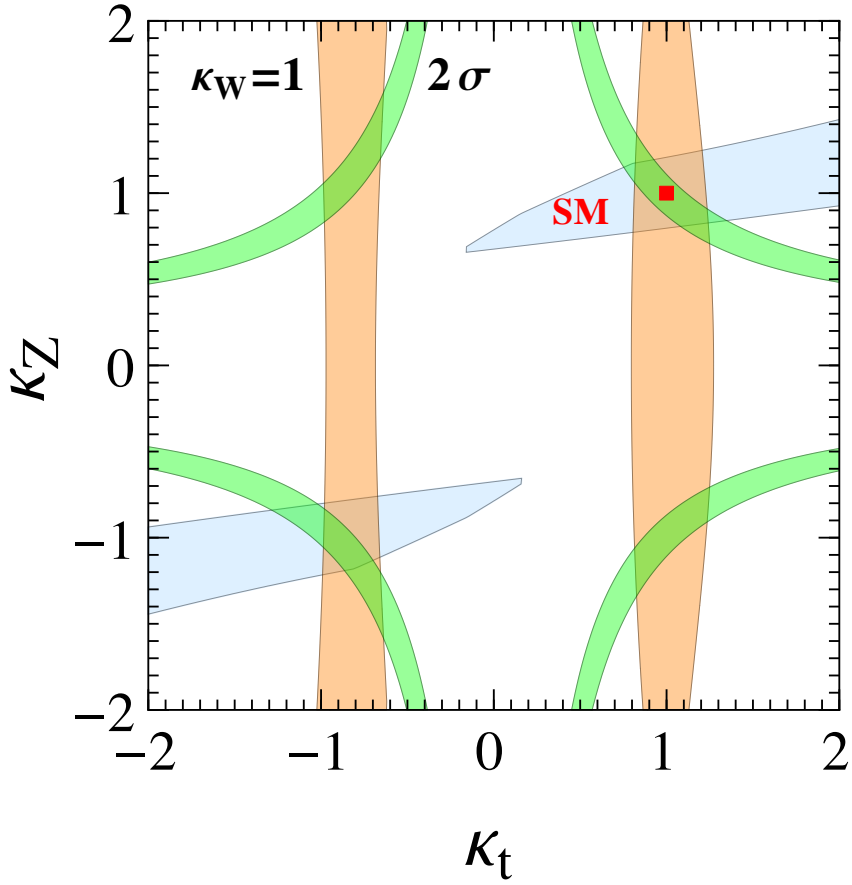
The cross sections will be large enhanced

Limits from current LHC

Orange: tth
Green: ggF, h->WW
Blue: th



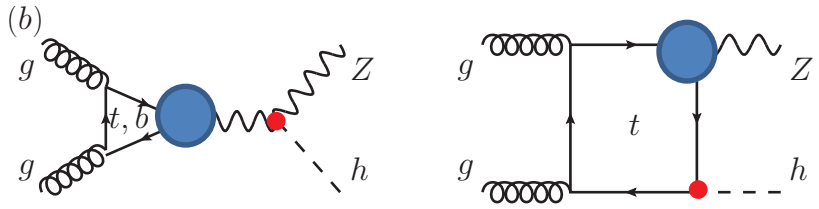
Orange: tth cross section
Green: ggF, h->ZZ
Blue: Zh



$\kappa_t \kappa_W < 0$ Excluded by current data $\kappa_t \kappa_Z < 0$

The impact of the Ztt coupling

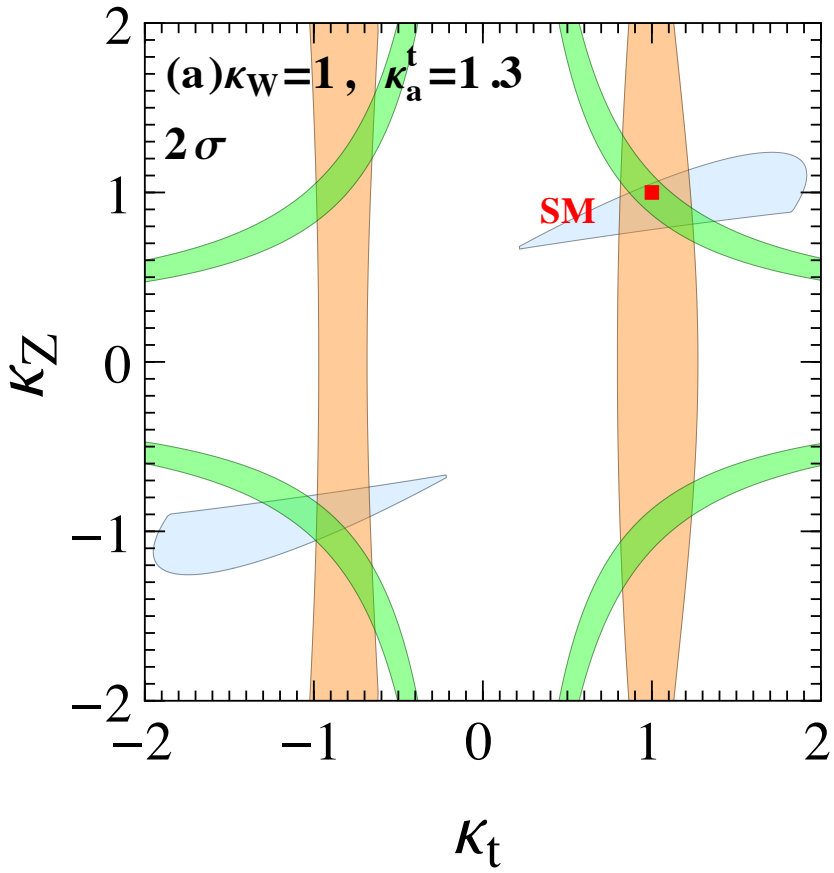
B. Yan, C.-P. Yuan, PRL 127 (2021)5,051801

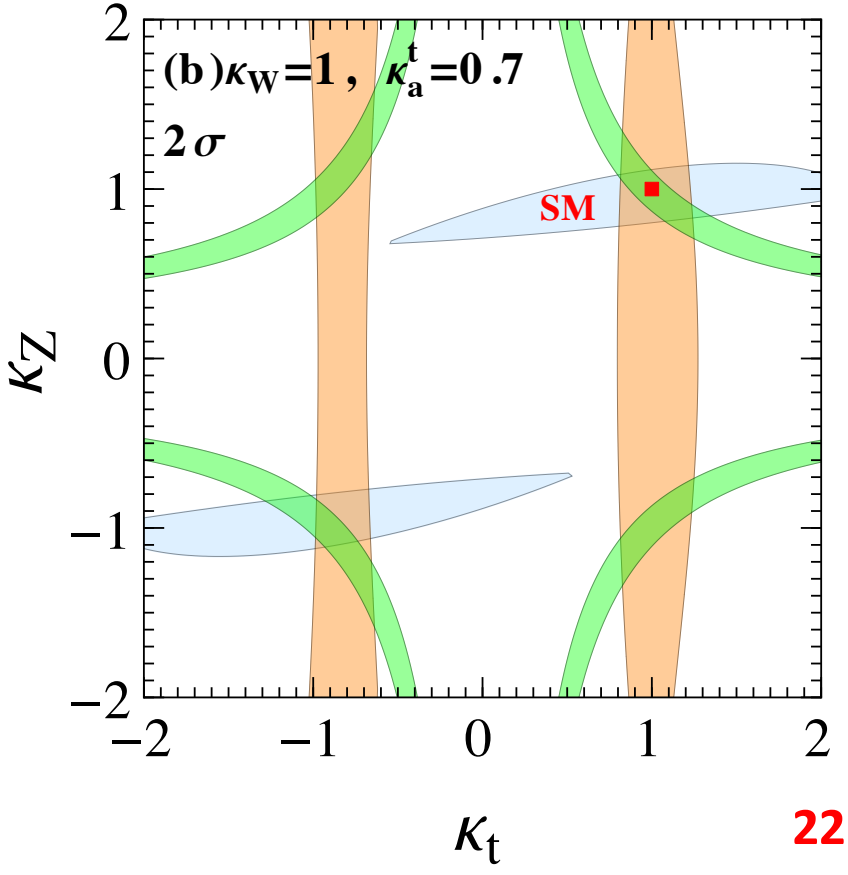


Charge conjugation invariance

Only axial-vector components

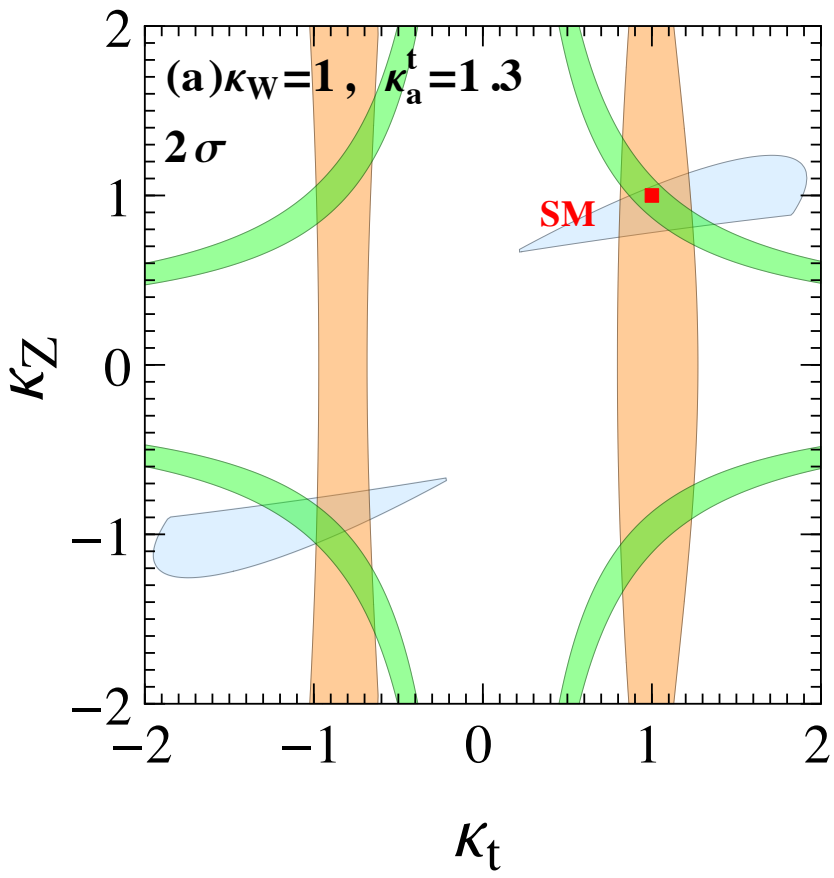
contribute to the cross section

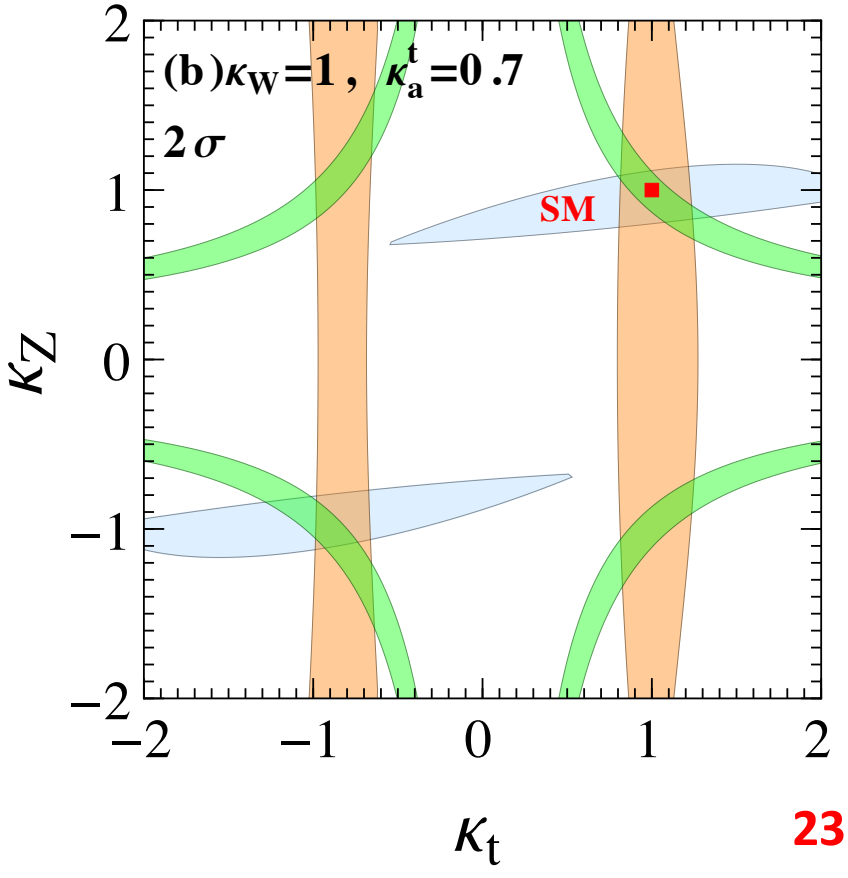




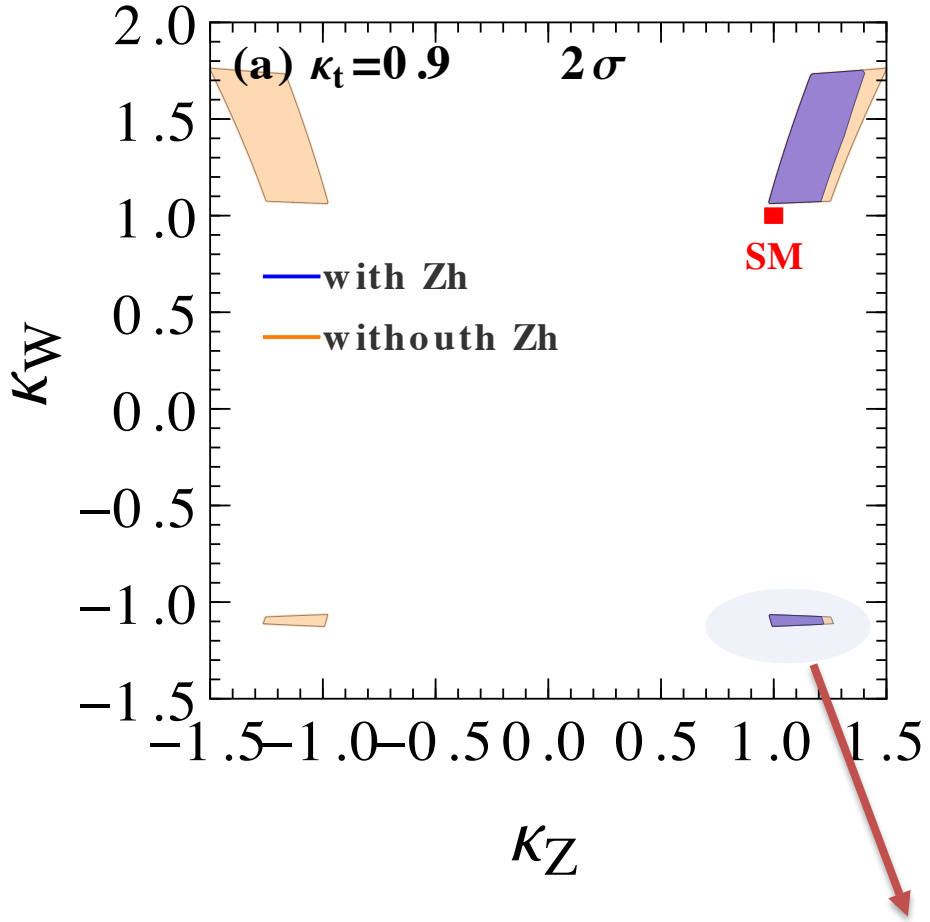
The impact of the Ztt coupling

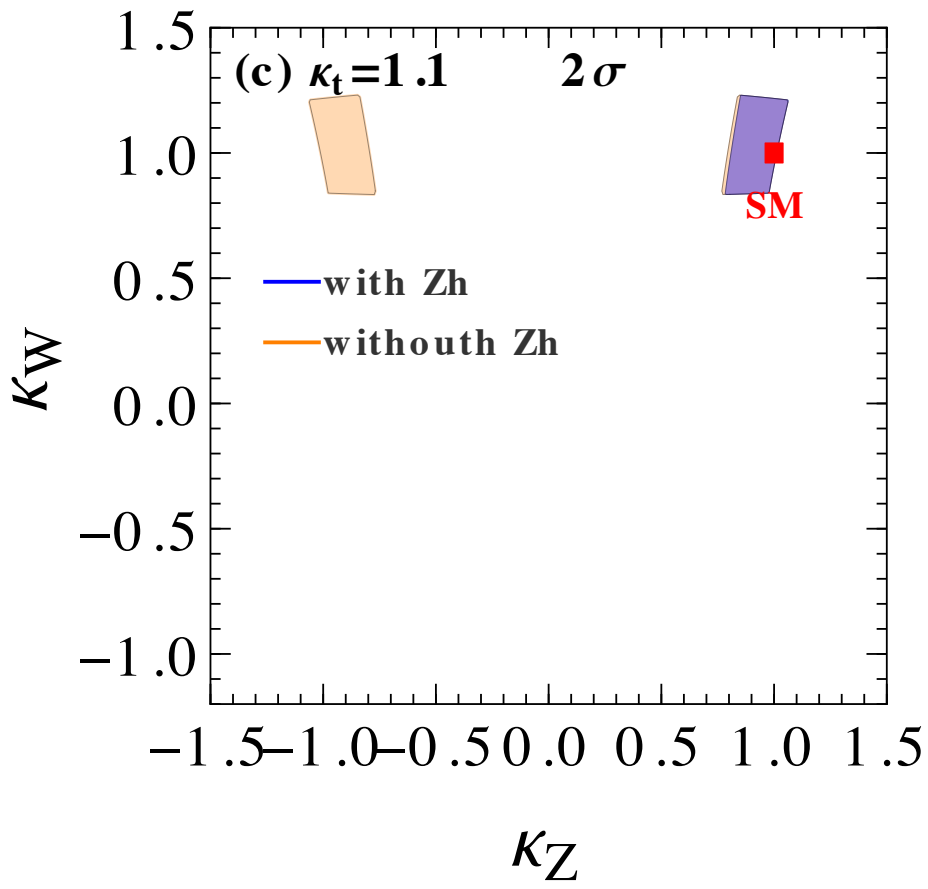
The conclusion is not sensitive to the assumption of the Ztt coupling





Limits from current LHC





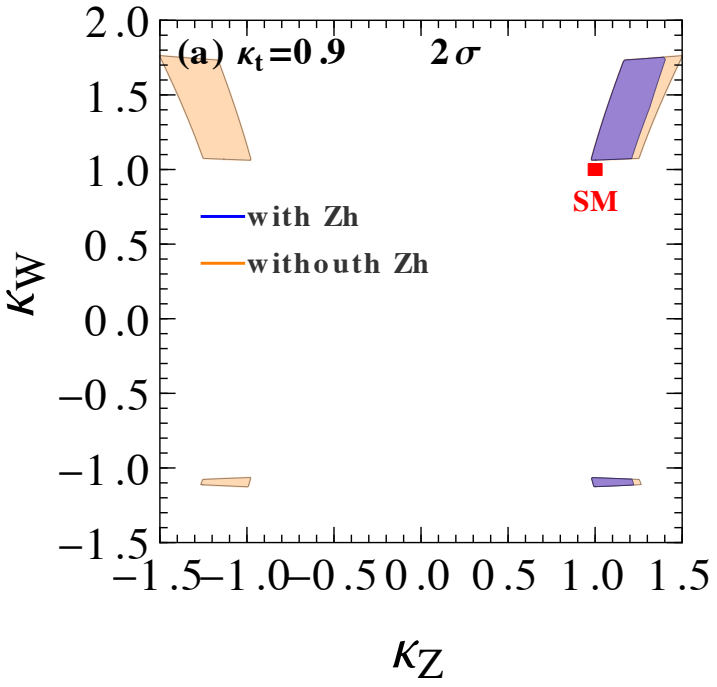
This region will be excluded soon at the LHC Run-3

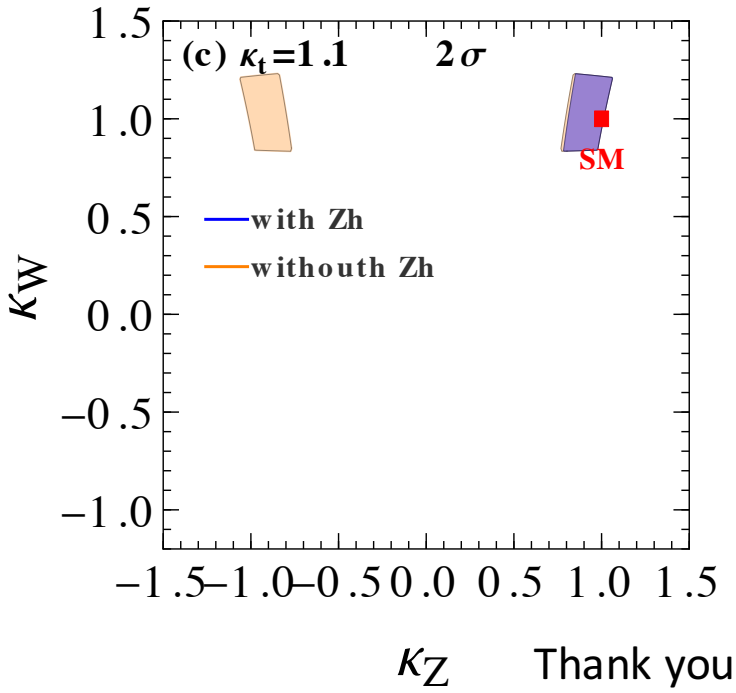
Summary

A. We proposed a new method to pin down the relative sign between hWW and hZZ couplings, which is a key part to verify the EWSB;

B. Combing th and Zh data at the 13 TeV LHC, the data favors the same sign of hWW and hZZ couplings.

C. This conclusion is not sensitive to the other possible new physics in Zh production.





Thank you!