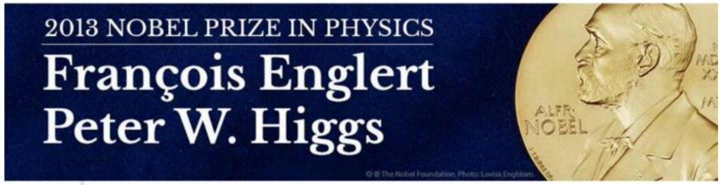
Theory overview: Collider Physics

Higgs properties and new physics beyond the SM

Bin Yan
Institute of High Energy Physics

The 9th China LHC Physics Workshop (CLHCP 2023)
Nov 16-20, 2023

The Era of the Higgs Physics

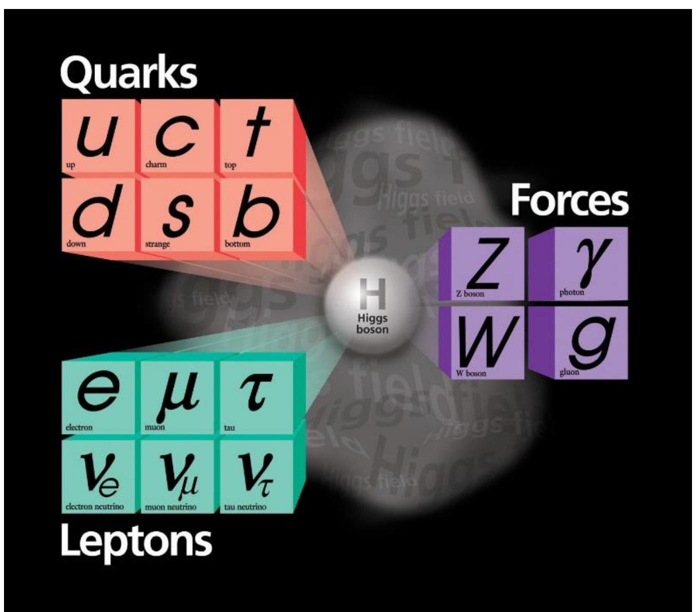


8 October 2013

The Royal Swedish Academy of Sciences has decided to award the Nobel Prize in Physics for 2013 to

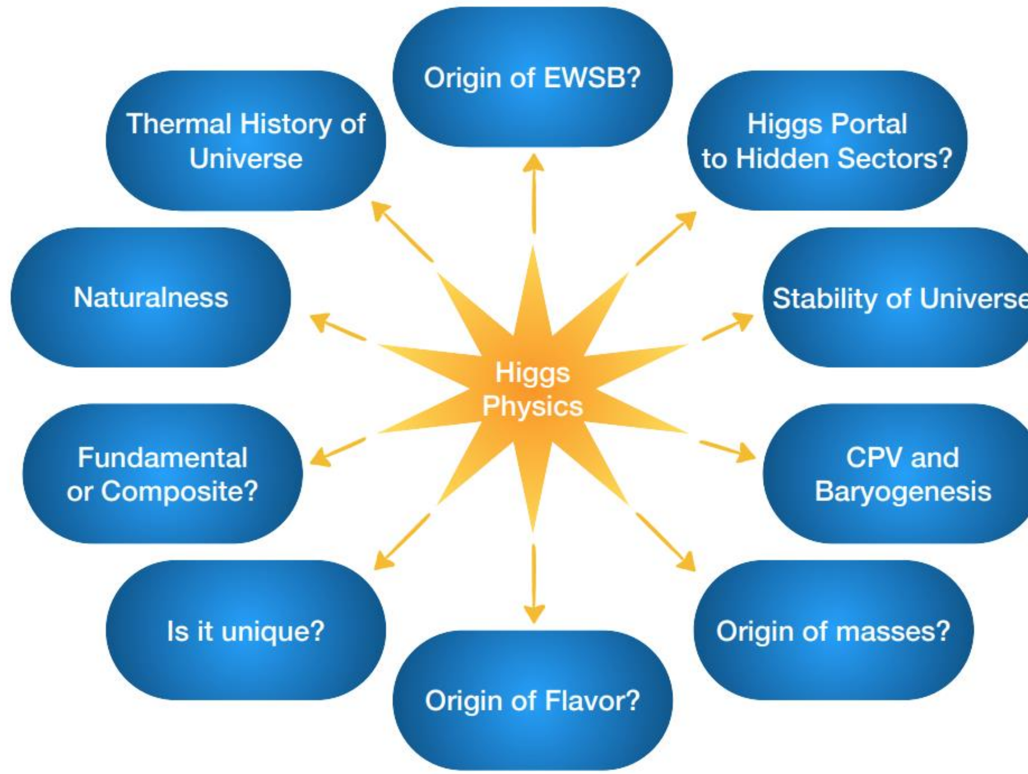
François Englert and Peter Higgs

"for the theoretical discovery of a mechanism that contributes to our understanding of the origin of mass of subatomic particles, and which recently was confirmed through the discovery of the predicted fundamental particle, by the ATLAS and CMS experiments at CERN's Large Hadron Collider"

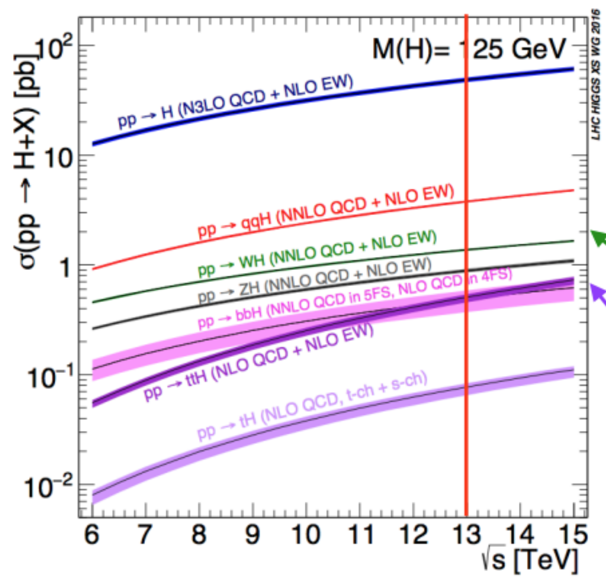


Understanding of origin of mass of subatomic particles

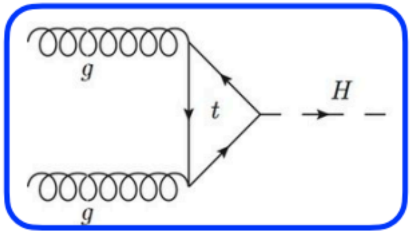
Snowmass 2021, 2209.07510



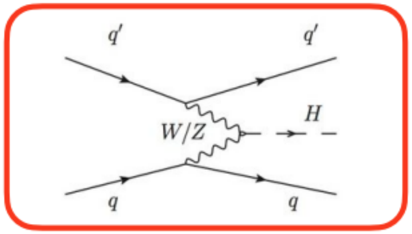
Higgs production @LHC



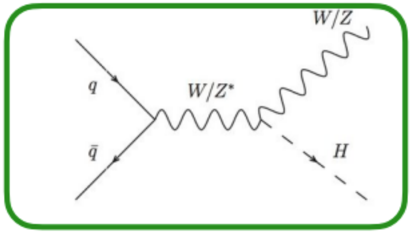
$\sqrt{s}$ (TeV)	Production cross section (in pb) for $m_H = 125\,\text{GeV}$					
	ggF	VBF	WH	ZH	$t\bar{t}H$	total
1.96	$0.95^{+17\%}_{-17\%}$	$0.065^{+8\%}_{-7\%}$	$0.13^{+8\%}_{-8\%}$	$0.079^{+8\%}_{-8\%}$	$0.004^{+10\%}_{-10\%}$	1.23
7	$16.9^{+5\%}_{-5\%}$	$1.24^{+2\%}_{-2\%}$	$0.58^{+3\%}_{-3\%}$	$0.34^{+4\%}_{-4\%}$	$0.09^{+8\%}_{-14\%}$	19.1
8	$21.4^{+5\%}_{-5\%}$	$1.60^{+2\%}_{-2\%}$	$0.70^{+3\%}_{-3\%}$	$0.42^{+5\%}_{-5\%}$	$0.13^{+8\%}_{-13\%}$	24.2
13	$48.6^{+5\%}_{-5\%}$	$3.78^{+2\%}_{-2\%}$	$1.37^{+2\%}_{-2\%}$	$0.88^{+5\%}_{-5\%}$	$0.50^{+9\%}_{-13\%}$	55.1
14	$54.7^{+5\%}_{-5\%}$	$4.28^{+2\%}_{-2\%}$	$1.51^{+2\%}_{-2\%}$	$0.99^{+5\%}_{-5\%}$	$0.60^{+9\%}_{-13\%}$	62.1



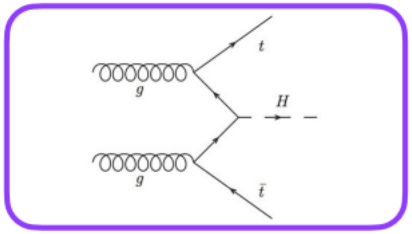
N³LO



N³LO



NNLO



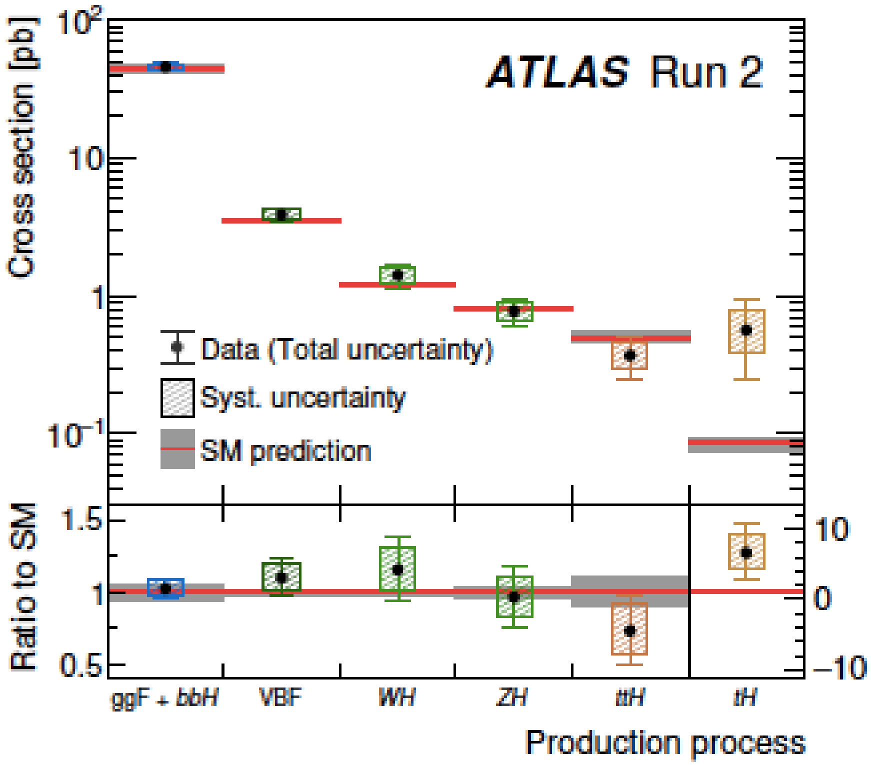
NLO + approx NNLO

G. Zanderighi Higgs 2022

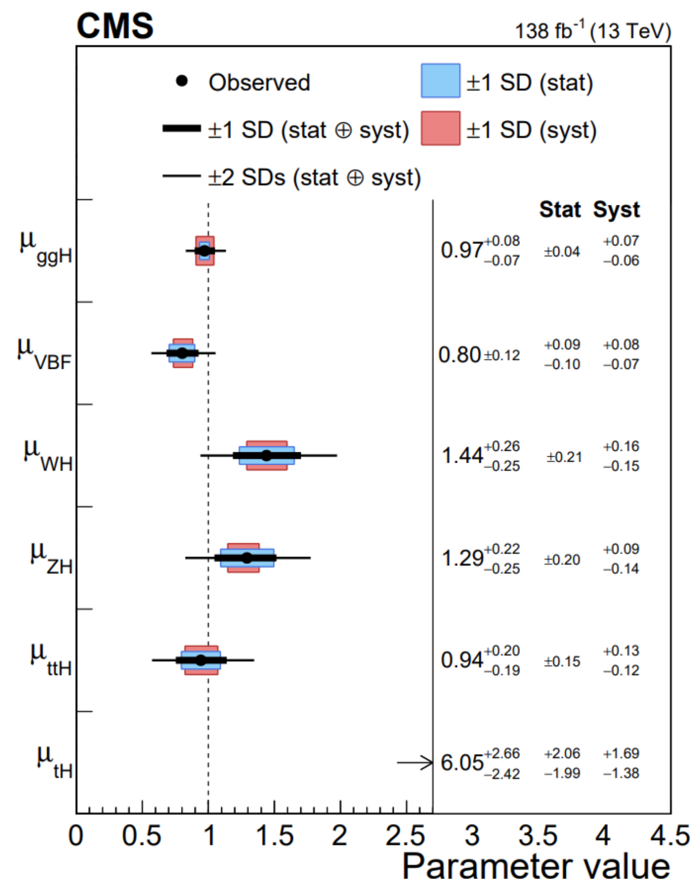
See HaiTao Li's talk

The measurements @ LHC

Nature 607 (2022)7917,52-59



Nature 607 (2022)7917,60-68



The data agrees with the SM prediction very well

See Xiaohu Sun's talk

The Framework for the Higgs physics

1. The κ framework for the couplings:

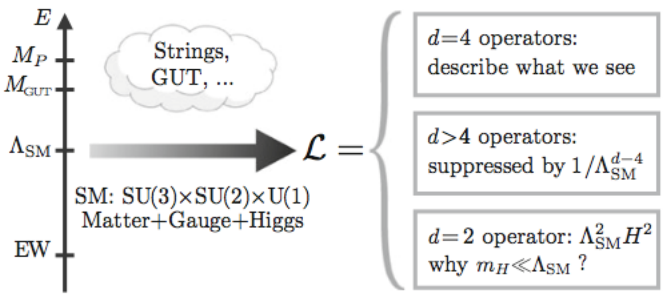
BSM physics is expected to affect the production modes and decay channels by a SM like interactions

2. The Standard Model Effective Field Theory

Linear realized EFT

Higgs is a fundamental particle

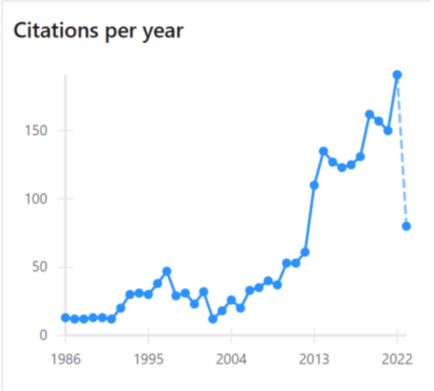
Weak interacting



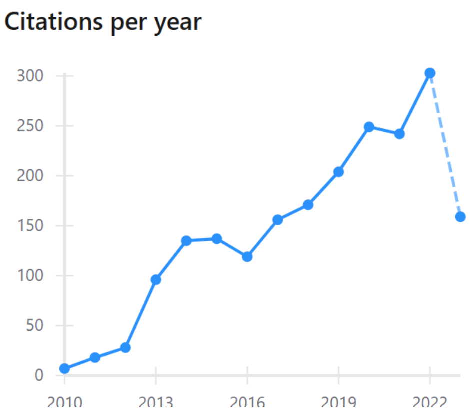
W. Buchuller, D. wyler 1986
B. Grzadkowski et al, 2010
L. Lehman, A. Marin, 2015
B. Henning et al, 2015
H-L. Li et al, 2020
Murphy, 2020
......

$$\mathcal{L} = \frac{C_6}{\Lambda^2}\mathcal{O}_6 + \frac{C_8}{\Lambda^4}\mathcal{O}_8 + \ldots$$

W. Buchuller, D. wyler 1986

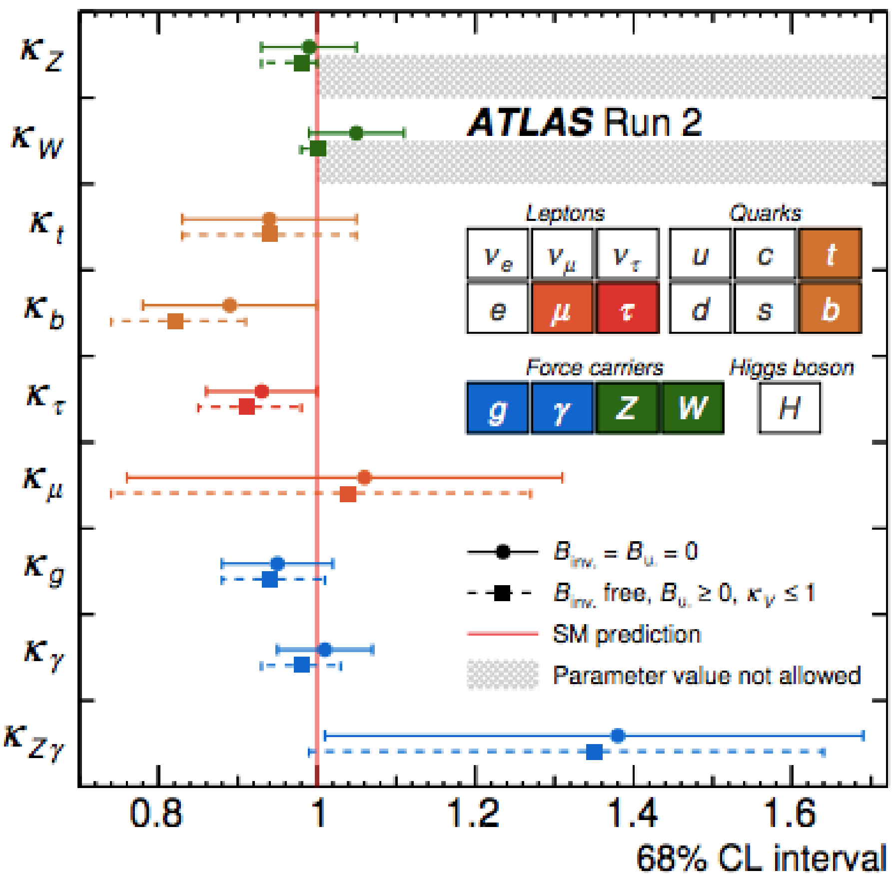


B. Grzadkowski et al, 2010

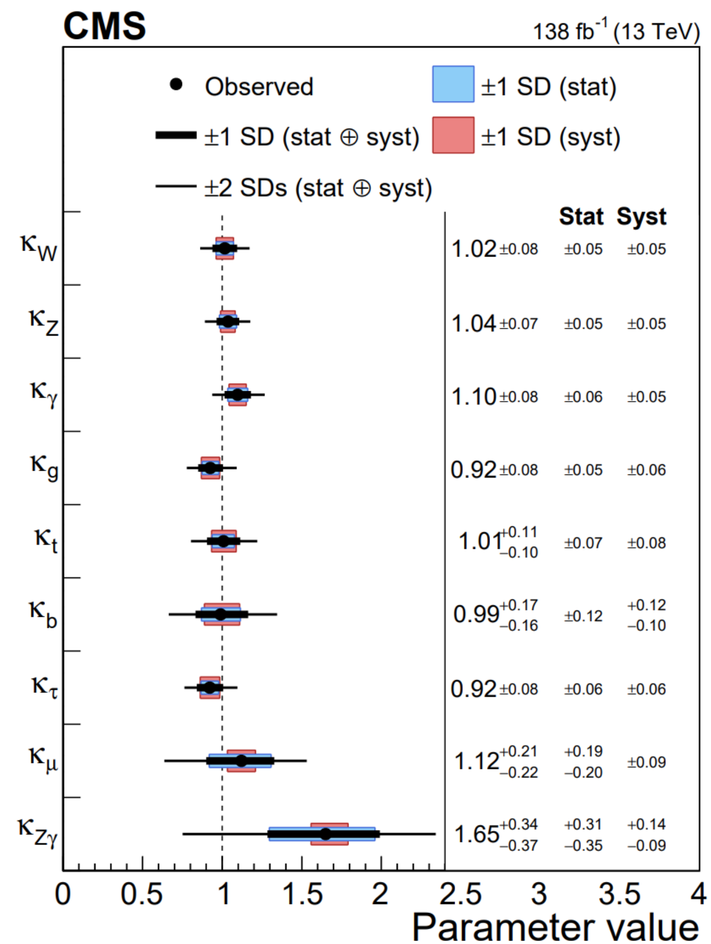


Higgs couplings @LHC

Nature 607 (2022)7917,52-59



Nature 607 (2022)7917,60-68

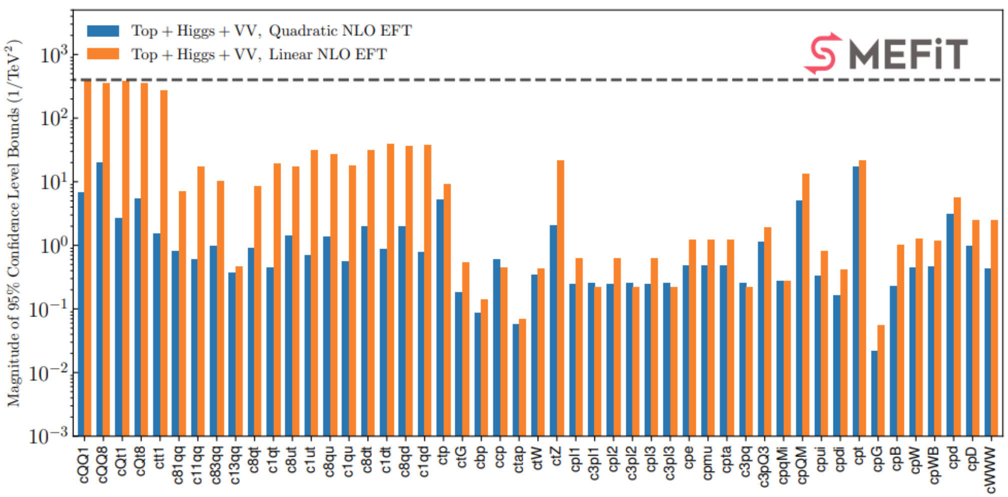


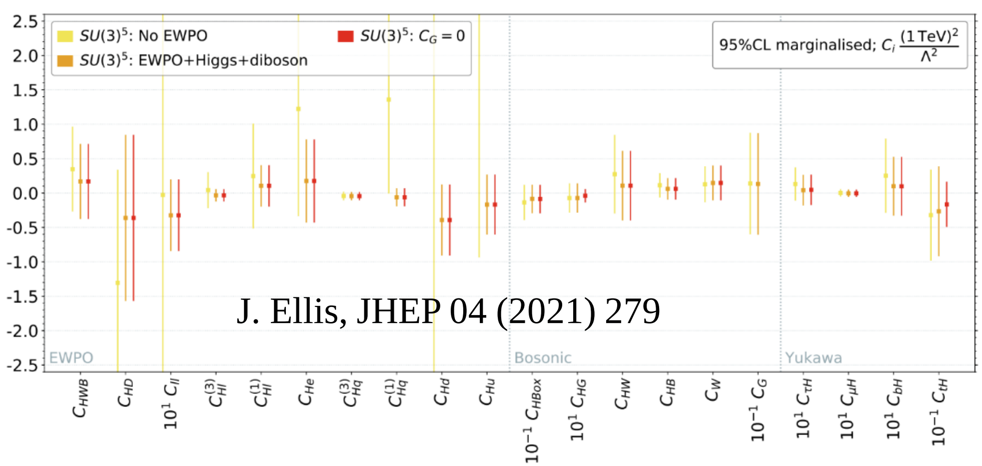
The data agrees with the SM prediction very well

See Xiaohu Sun's talk

Global Analysis @ SMEFT

SMEFiT Collaboration, JHEP 11 (2021) 089





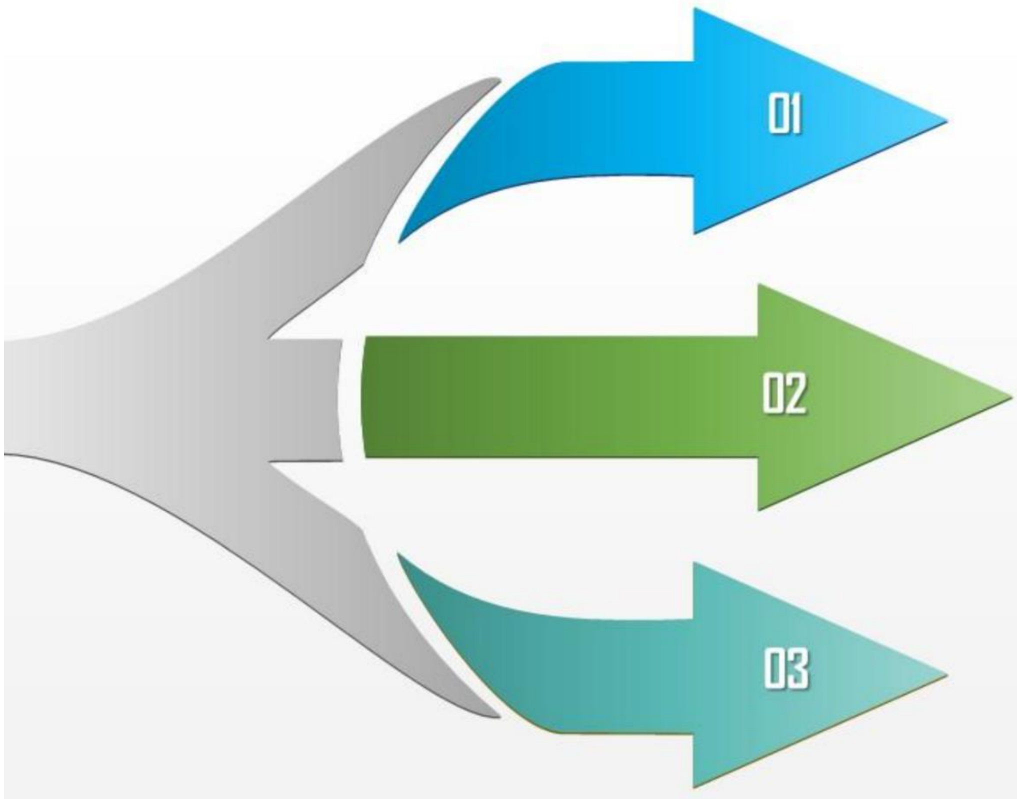
J. Ellis, JHEP 04 (2021) 279

The SMEFT approach allows for the combination

- Higgs data
- Electroweak precision observables
- Diboson production
- Top quark Physics

SMEFT is becoming one of the standard tool for the LHC experimental analysis

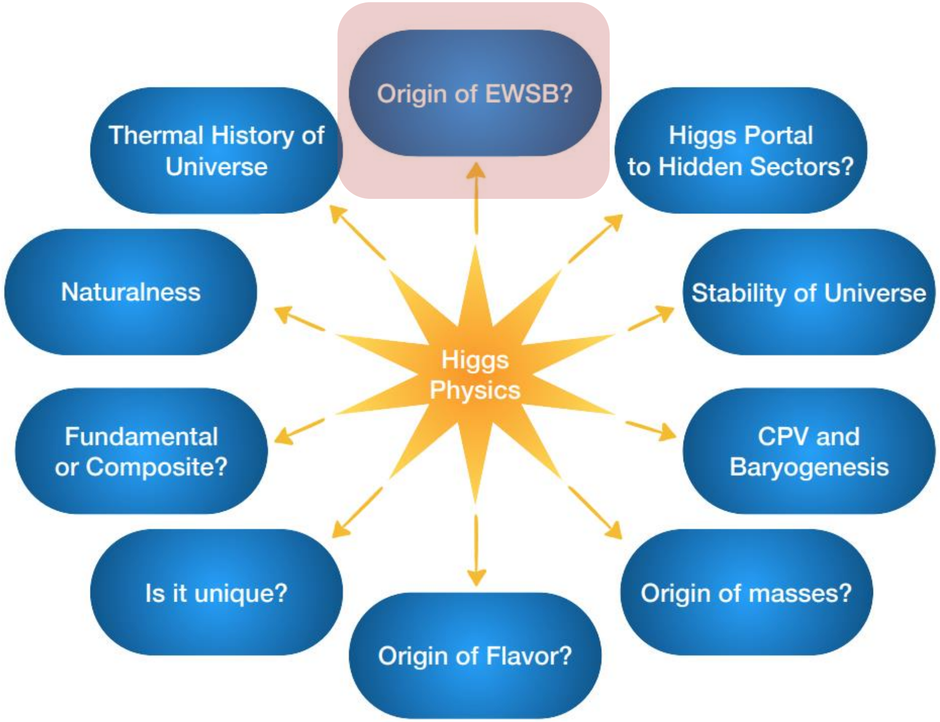
So, what's the next step for the Higgs physics (BSM) from the theoretical point of view?



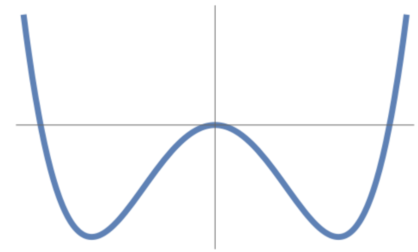
- Global analysis with more processes; the combination of low energy and high energy measurements
- QCD and EW correction to reduce the theoretical uncertainties
- New observables and new measurements

Topics are chosen based on my personal perspective and apologize if your work/topics are not covered in this talk

Testing the EWSB @ LHC



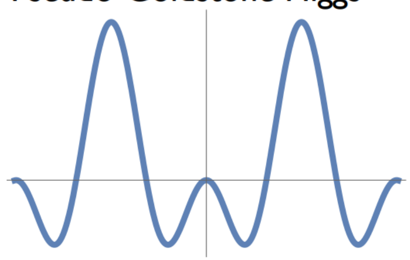
Landau-Ginzburg Higgs



$$V(\phi) = -m^2\phi^\dagger\phi + \lambda\left(\phi^\dagger\phi\right)^2$$

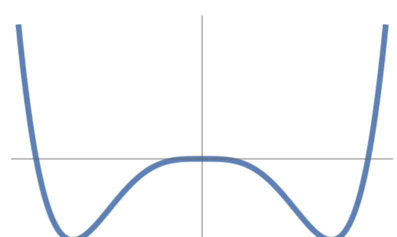
Agrawal, Saha, Xu, Yu, Yuan, 2019

Pseudo-Goldstone Higgs



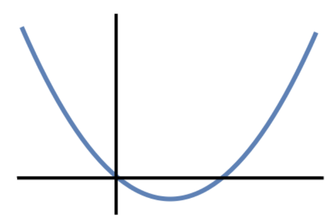
$$V(\phi) = a\sin^2(\phi/f) + b\sin^4(\phi/f)$$

Coleman Weinberg Higgs



$$V(\phi) = \lambda(\phi^\dagger\phi)^2 + \epsilon(\phi^\dagger\phi)^2\log\frac{\phi^\dagger\phi}{\mu^2}$$

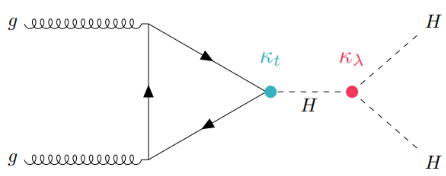
Tadpole-induced Higgs

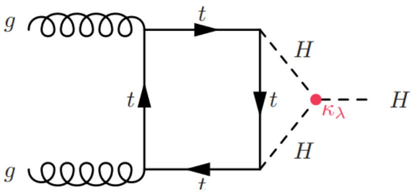


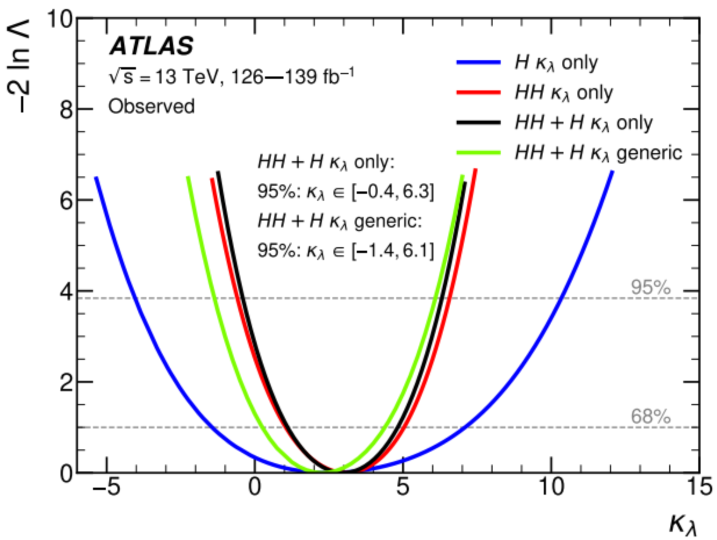
$$V(\phi) = -\mu^3\sqrt{\phi^\dagger\phi} + m^2\phi^\dagger\phi$$

Testing the EWSB @ LHC

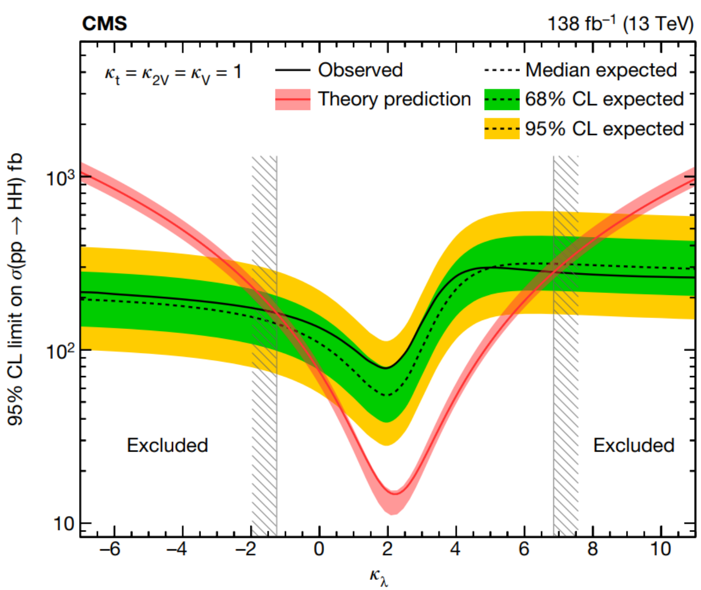
To determine the Higgs potential shape is challenge!







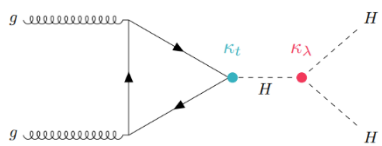
ATLAS, PRD108 (2023)5, 052003



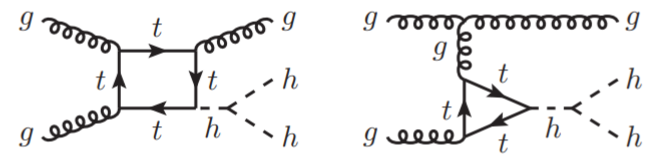
Nature 607 (2022) 60

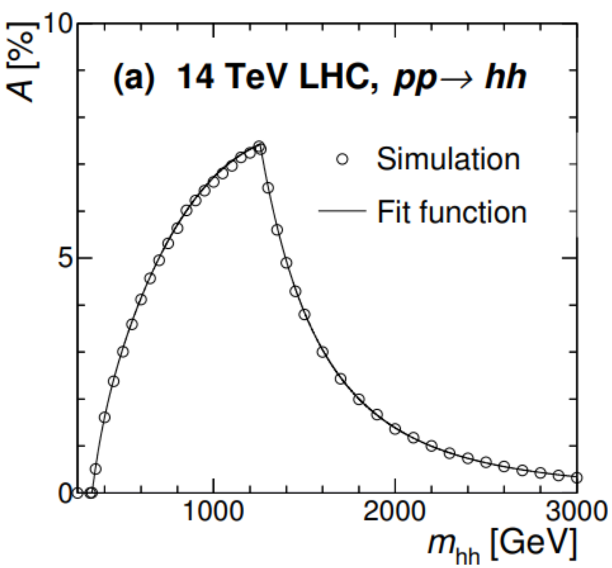
Testing the EWSB @ LHC

Current experimental searches mainly focus on the high di-Higgs invariant mass region

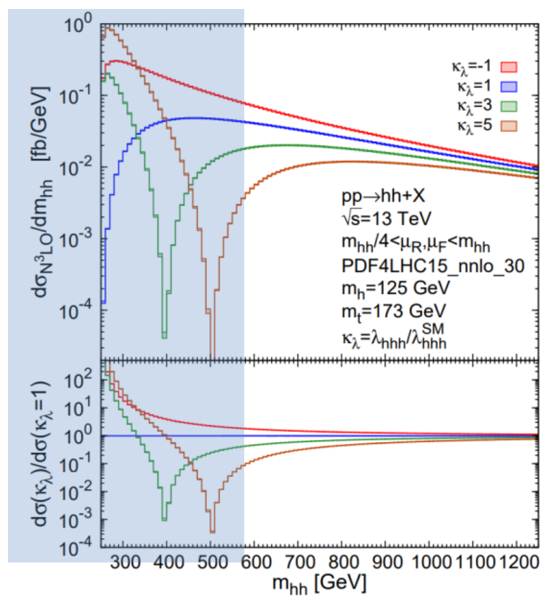


The low di-Higgs invariant mass region is more sensitive to the Higgs shape

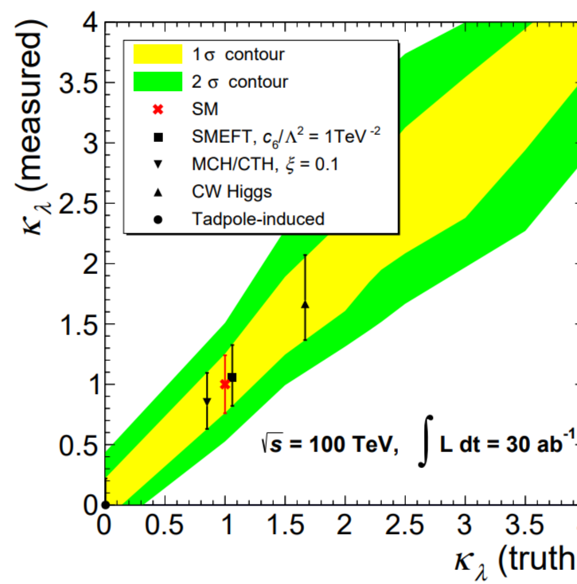




Q.-H. Cao, Bin Yan, D.-M. Zhang, H. Zhang, PLB 752 (2016) 285-290

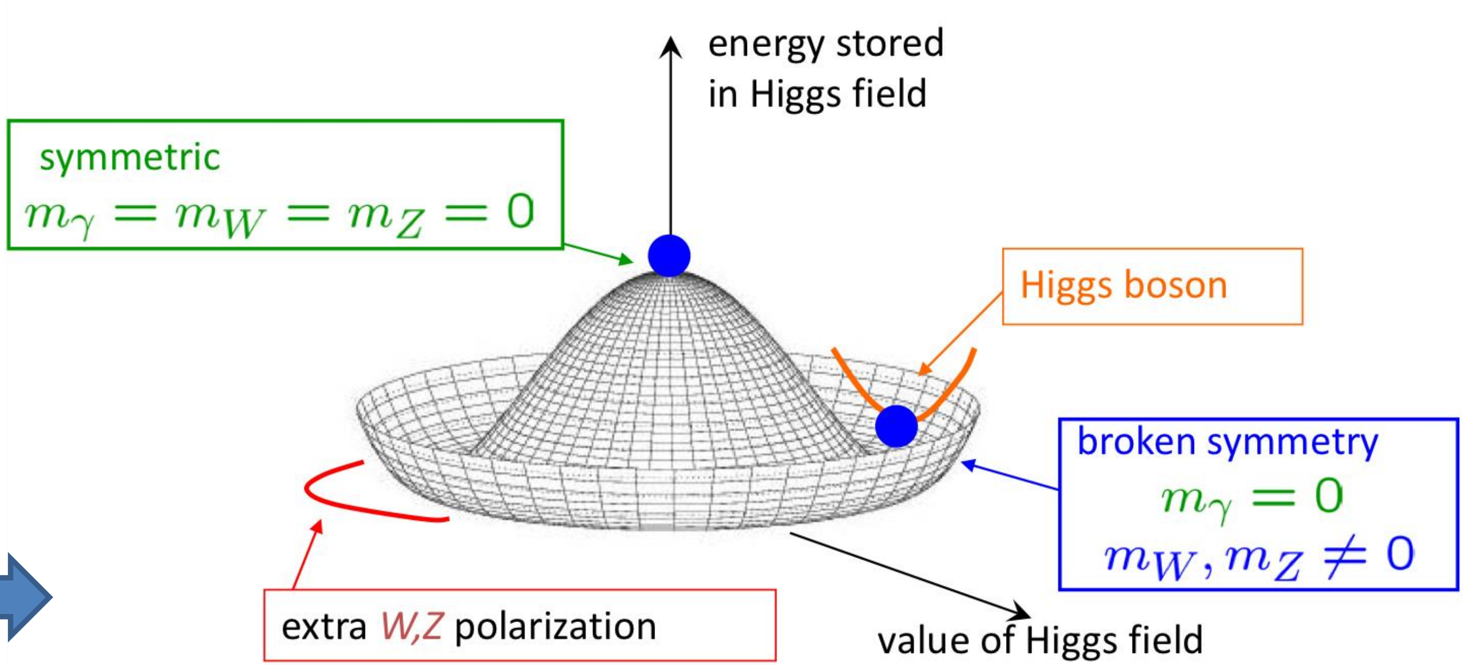


L. B. Chen, H. T. Li, H. S. Shao, J. Wang, PLB 803 (2020) 135292, JHEP 03 (2020) 072



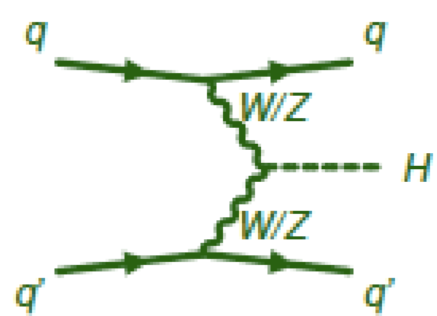
K. Chai, J.-H. Yu, H. Zhang, PRD 107(2023) 5,055031

Testing the EWSB @ LHC



Precisely determine the Higgs gauge couplings are also important for testing the EWSB

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

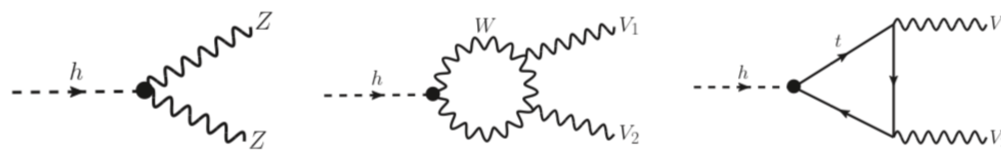


Higgs couplings and EWSB

- The magnitude of the Higgs gauge couplings
- The relative sign between hWW and hZZ couplings

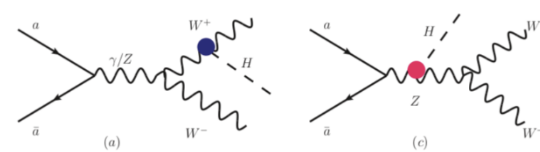
Y. Chen et al, PRL 2016

- ☐ Interference between tree and loop level in Higgs decay

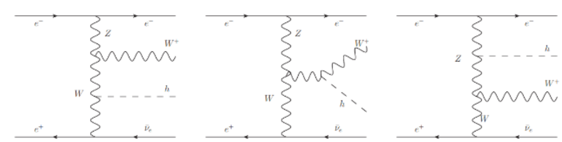


- ☐ Lepton Colliders

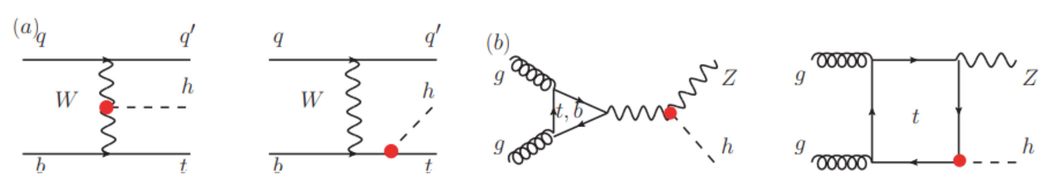
C.W Chiang, X. G. He and G. Li, JHEP08(2018) 126



D. Stolarski, Y. Wu, PRD 102 (2020)3, 033006



- ☐ th and Zh production

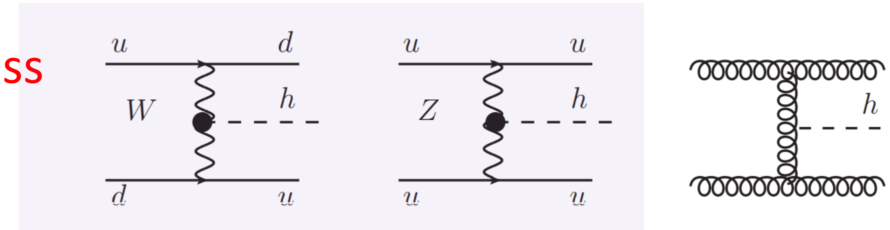


The data favors the same sign

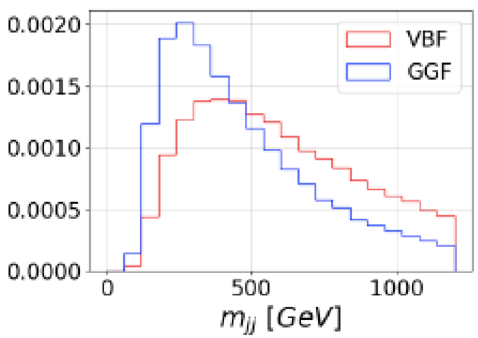
K. P. Xie and Bin Yan, PLB 820 (2021) 136515

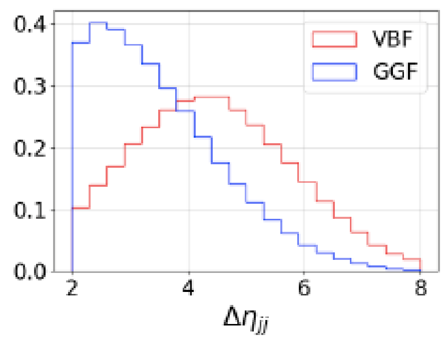
Higgs couplings @ VBF

VBF Higgs production is the main process to verify the Higgs gauge couplings



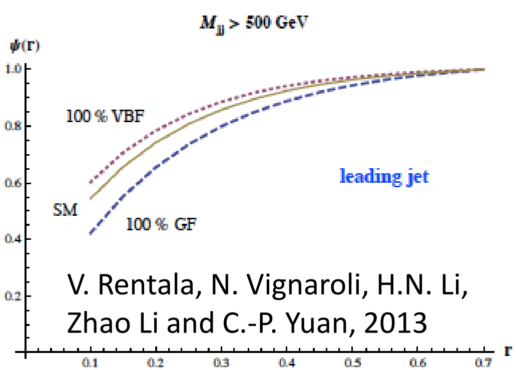
- The rapidity gap and the invariant mass of the two jets





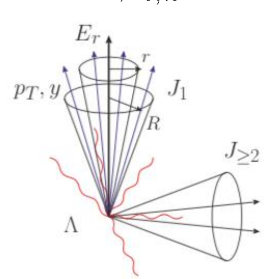
V.D. Bargeer, K.m.Cheung. T. Han, J. Ohnemus and D. Zeppenfeld, 1991
N. Kauer, T. Plehn, D. L. Rainwater and D. Zeppenfeld, 2001
……

- Soft gluon radiation effects: Jet energy profile, TMD effects

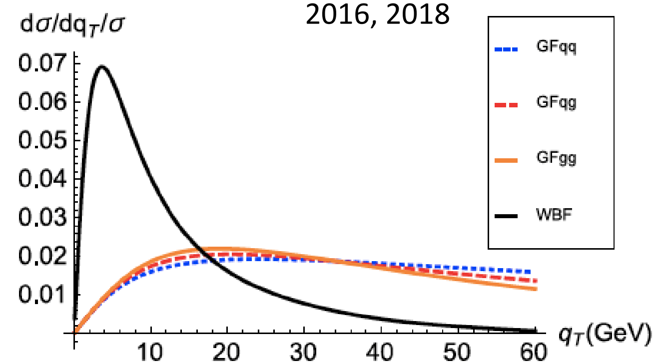


V. Rentala, N. Vignaroli, H.N. Li, Zhao Li and C.-P. Yuan, 2013

$$\Psi_J(r) = \frac{\sum_{i,d_{i,\hat{n}}<r} E_T^i}{\sum_{i,d_{i,\hat{n}}<R} E_T^i}$$

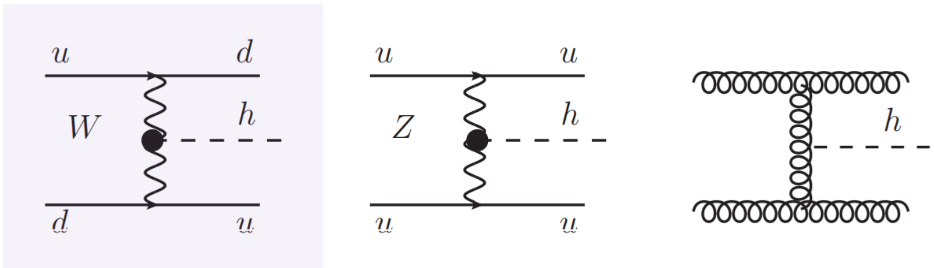


P. Sun, C.-P. Yuan and F. Yuan, 2016, 2018



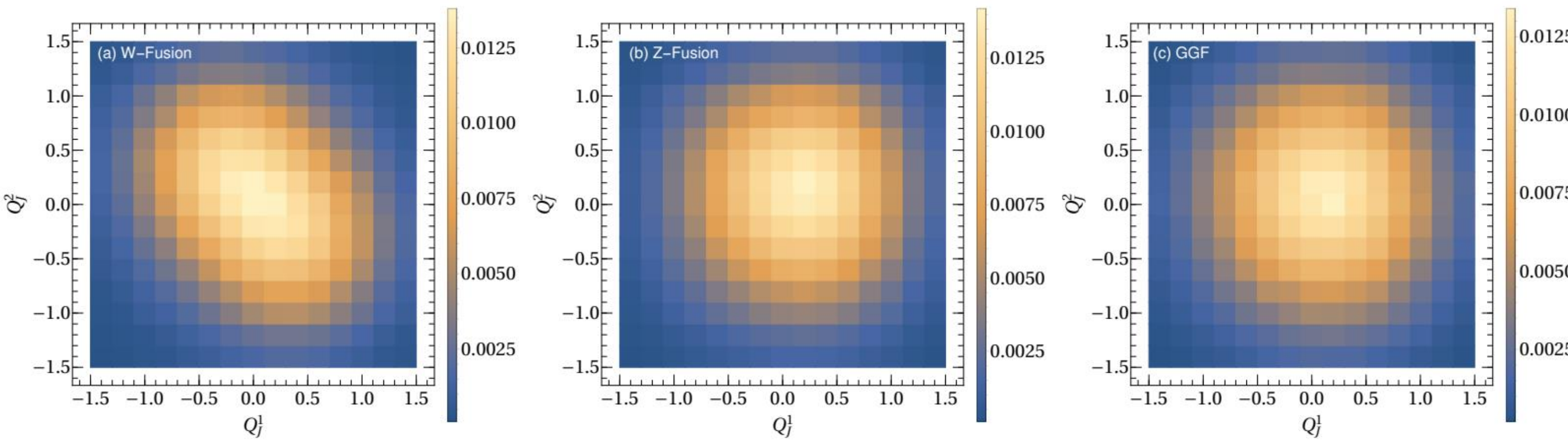
Higgs coupings @ VBF

Separating the W boson's contribution from the VBF Higgs production is an important and challenge task for determining the Higgs gauge coupling



H. T. Li, Bin Yan, C.-P. Yuan, PRL 131 (2023) 4, 041802

The key observable: Jet Charge



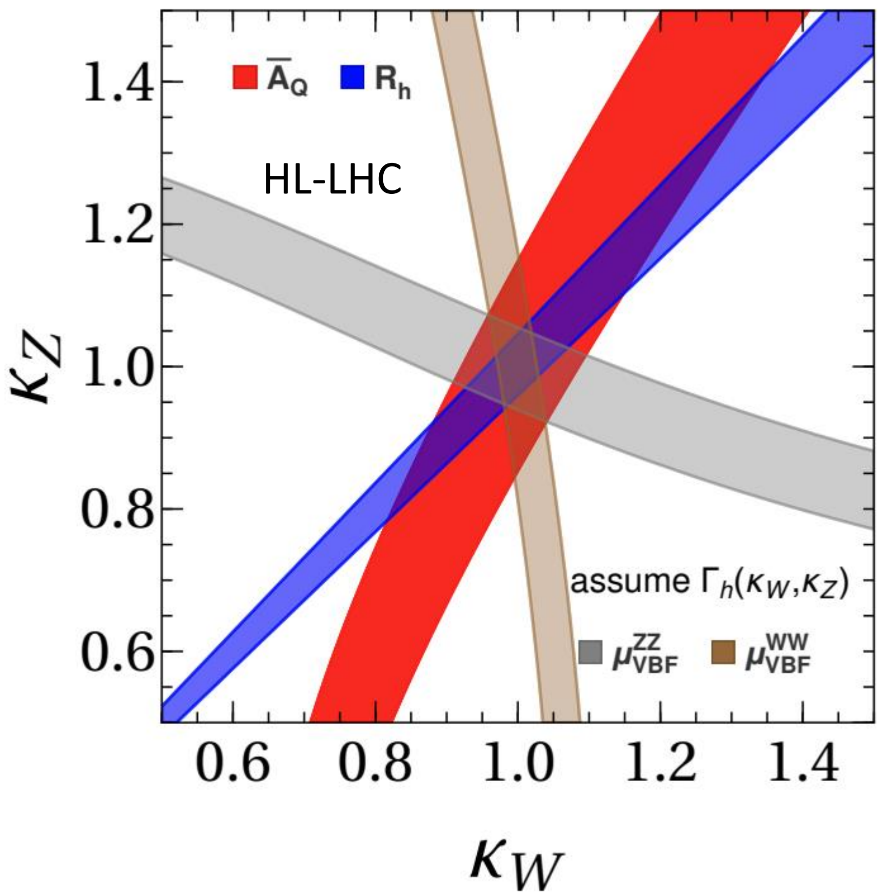
opposite sign for the two jet charges

same or opposite sign

the sign of the jet charge is arbitrary

Higgs couplings @ VBF

$$h \to 4\ell/2\ell 2v_\ell$$



$$Q^{(\pm)} = |Q_J^1 \pm Q_J^2|$$

$$\overline{A}_Q^{\text{tot}} = \frac{f_W\langle Q^{(-)}\rangle_W + f_Z\langle Q^{(-)}\rangle_Z + f_G\langle Q^{(-)}\rangle_G}{f_W\langle Q^{(+)}\rangle_W + f_Z\langle Q^{(+)}\rangle_Z + f_G\langle Q^{(+)}\rangle_G}$$

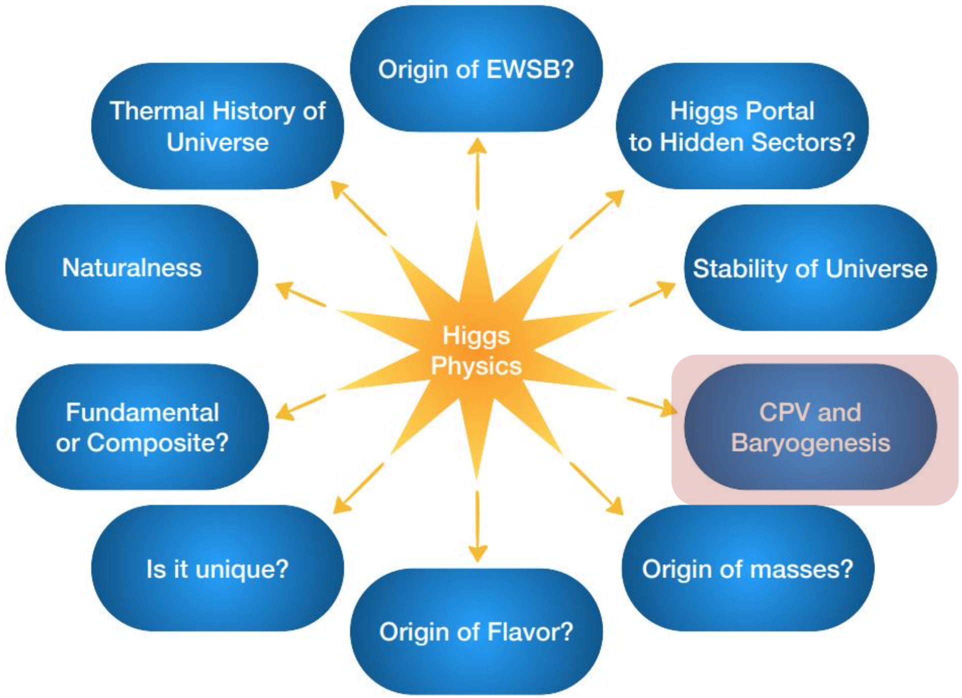
$$R_h = \frac{\mu(gg \to h \to WW^*)}{\mu(gg \to h \to ZZ^*)} = \frac{\kappa_W^2}{\kappa_Z^2}$$

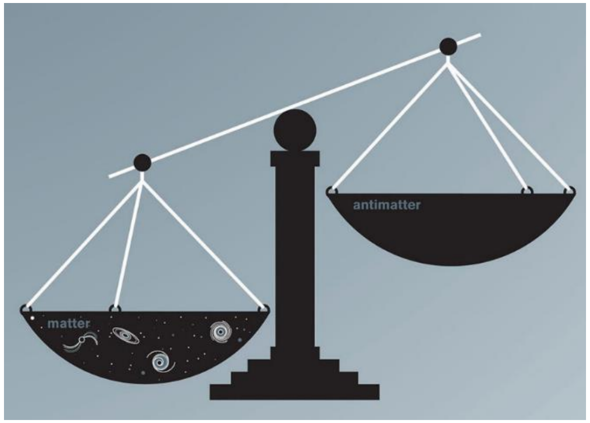
$$\kappa_V = \frac{g_{hVV}}{g_{hVV}^{\text{SM}}}$$

H. T. Li, Bin Yan, C.-P. Yuan, PRL 131 (2023) 4, 041802

The limits from Rh and jet charge asymmetry are not depending on the assumption of the Higgs width

Higgs CP violation





Sakharov Criteria (1967)

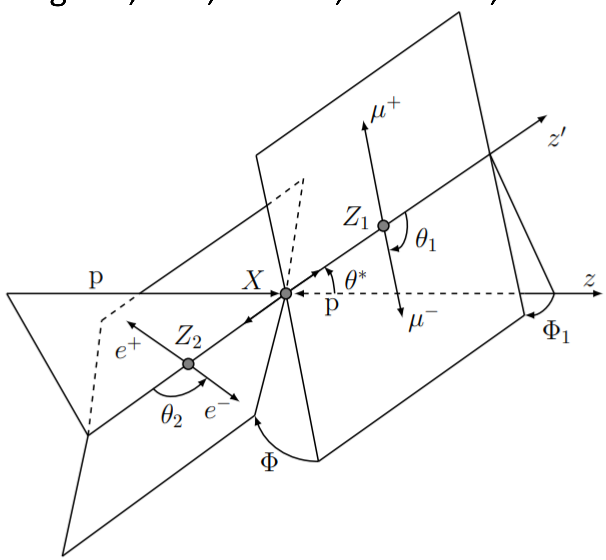
- B violation
- C & CP violations
- Departure from the equilibrium

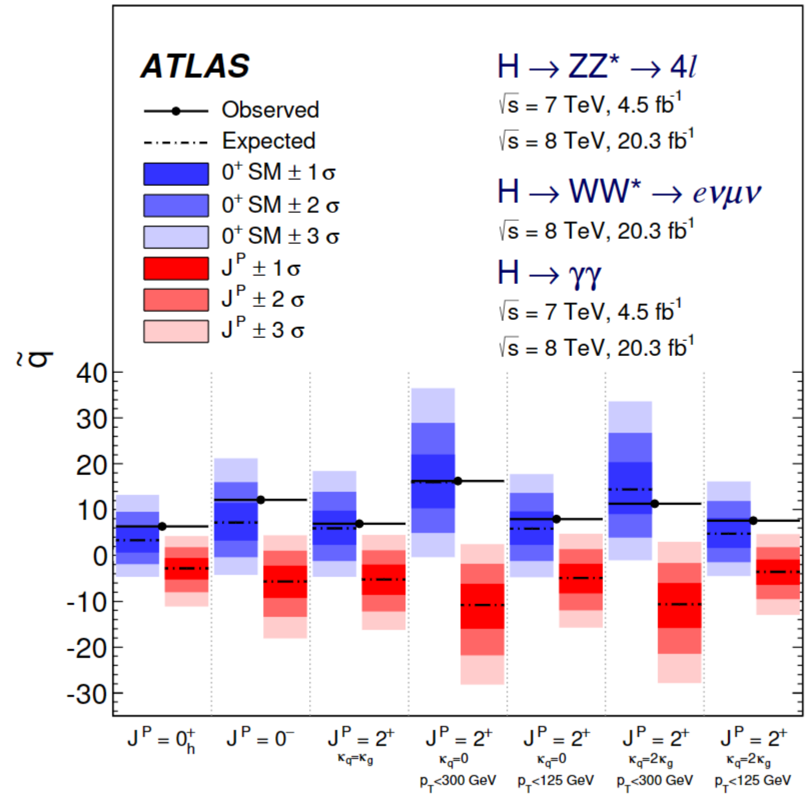
Higgs CP violation

PDG 2022

Higgs boson CP property:

e.g. Bolognesi, Gao, Gritsan, Melnikov, Schulze, 2012





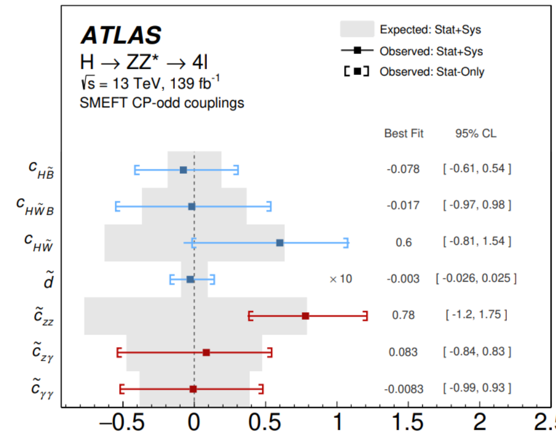
- A purely CP-odd Higgs has been excluded
- A CP-mixture Higgs boson is still possible

Higgs CP violation

- CP-odd interactions with gauge bosons (loop induced operators)

ATLAS,2304.09612

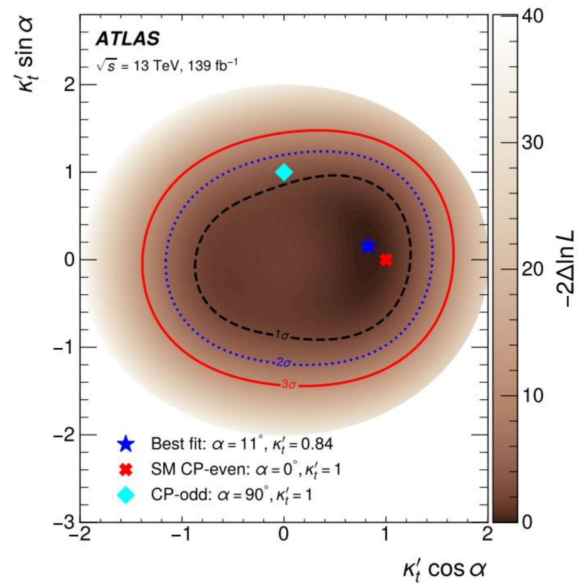
Operator	Structure	Coupling
Warsaw Basis		
$O_{\Phi\tilde{W}}$	$\Phi^\dagger\Phi\tilde{W}^I_{\mu\nu}W^{\mu\nu I}$	$c_{H\widetilde{W}}$
$O_{\Phi\tilde{W}B}$	$\Phi^\dagger\tau^I\Phi\tilde{W}^I_{\mu\nu}B^{\mu\nu}$	$c_{H\widetilde{W}B}$
$O_{\Phi\tilde{B}}$	$\Phi^\dagger\Phi\tilde{B}_{\mu\nu}B^{\mu\nu}$	$c_{H\widetilde{B}}$
Higgs Basis		
$O_{hZ\tilde{Z}}$	$hZ_{\mu\nu}\tilde{Z}^{\mu\nu}$	$\tilde{c}_{zz}$
$O_{hZ\tilde{A}}$	$hZ_{\mu\nu}\tilde{A}^{\mu\nu}$	$\tilde{c}_{z\gamma}$
$O_{hA\tilde{A}}$	$hA_{\mu\nu}\tilde{A}^{\mu\nu}$	$\tilde{c}_{\gamma\gamma}$



- CP-odd interactions with fermions

Gunion, He, PRL. 76, 4468 (1996)
Boudjema, Godbole, Guadagnolo, Mohan, PRD 92, 015019 (2015)
Mileo, Kiers, Szynkman, Crane, Gegner, JHEP 07, 056 (2016)
Gritsan, Rntsch, Schulze, Xiao, PRD 94, 055023 (2016)
S. Amor Dos Santos et al, PRD 96, 013004 (2017)
Kobakhidze, Liu, Wu, Yue, PRD 95 (2017) 1, 015016
Gouveia et al, 1801.04954
Gonalves, Kong, Kim, JHEP 06, 079 (2018)
Ren, Wu, Yang, 1901.05627
ATLAS, PRL 125 (2020) 6,061802
CMS, PRL 125 (2020) 6,061801
Q.-H. Cao, K.-P. Xie, H. Zhang , R. Zhang,CPC45 (2021)2,023117
Zhite Yu and C.-P. Yuan, 2211.00845
…

Apologize if not including your papers

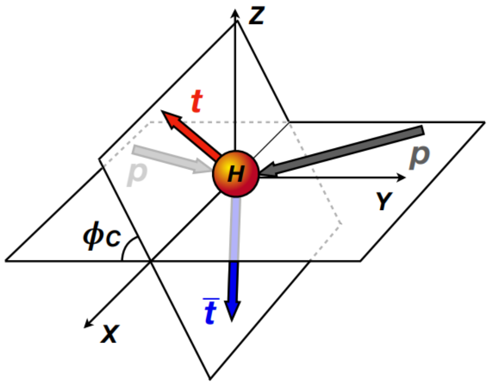


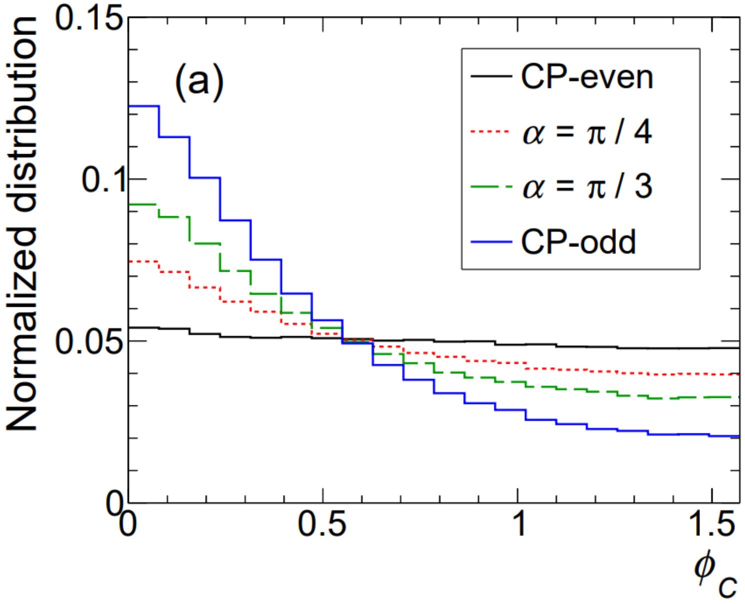
ATLAS： 2303.05974
CMS： 2208.02686

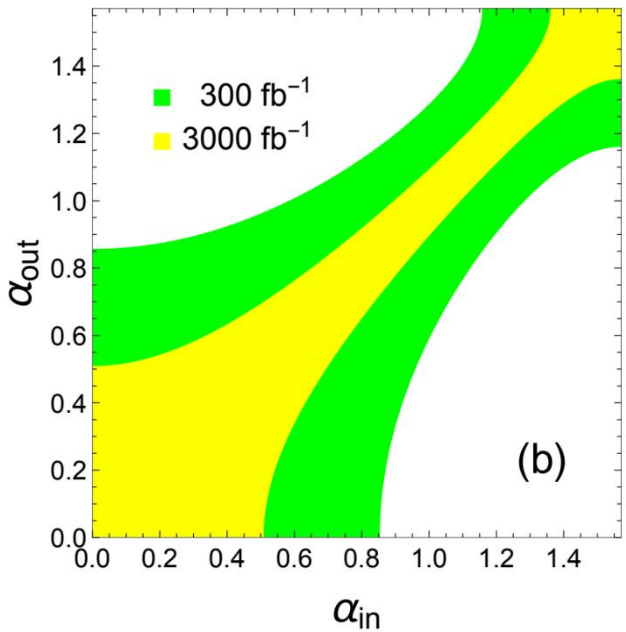
Higgs CP violation

$$\mathscr{L} = y_f h\bar{f}(\cos\alpha_f + i\gamma_5 \sin\alpha_f)f$$

$$\phi_C = \arccos\left|(\mathbf{n}_{p_1}\times\mathbf{n}_{p_2})\cdot(\mathbf{n}_t\times\mathbf{n}_{\bar{t}})\right|$$



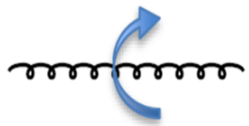


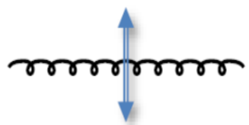


Q.-H. Cao, K.-P. Xie, H. Zhang , R. Zhang,CPC45 (2021)2,023117

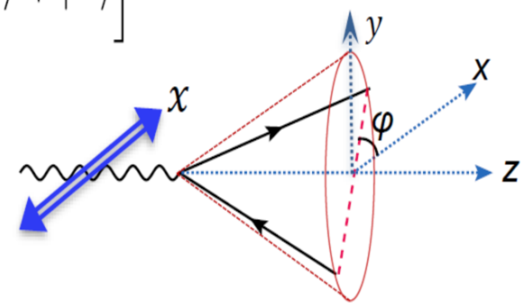
New polarization observables

- Linear polarization vs. helicity/circular polarization

helicity pol.  $|\pm 1\rangle$

linear pol.  $|x\rangle = -\frac{1}{\sqrt{2}}\Big[|+\rangle - |-\rangle\Big], \quad |y\rangle = \frac{i}{\sqrt{2}}\Big[|+\rangle + |-\rangle\Big]$

$$|e^{+i\phi} \pm e^{-i\phi}|^2 \to 2(1 \pm \cos 2\phi)$$



Interference of helicity λ_1 and λ_2 causes azimuthal distributions

$$\cos(\lambda_1 - \lambda_2)\phi, \quad \sin(\lambda_1 - \lambda_2)\phi$$

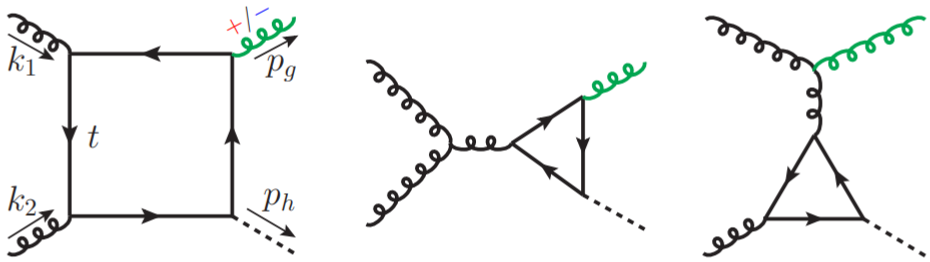
CP even **CP odd**

Useful probes of new physics

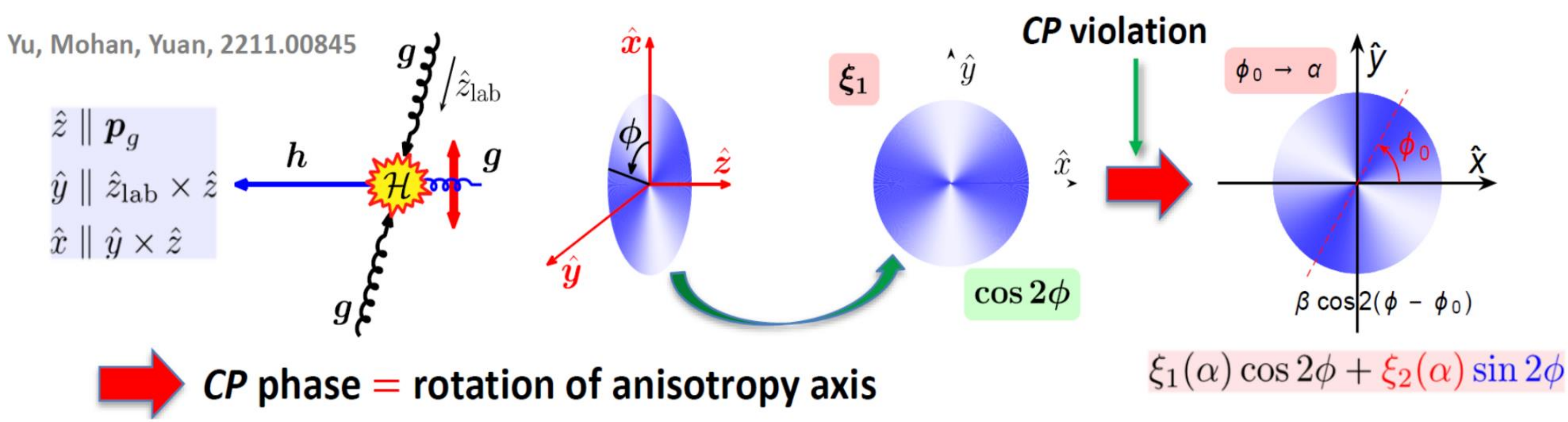
C.-P. Yuan's talk @ MBI 2023

New polarization observables

Linear polarization of gluon



$$\rho_{\lambda\lambda'} = \frac{1}{2}\left(1+\boldsymbol{\xi}\cdot\boldsymbol{\sigma}\right)_{\lambda\lambda'} = \frac{1}{2}\begin{pmatrix} 1+\xi_3 & \xi_1 - i\,\xi_2 \\ \xi_1 + i\,\xi_2 & 1-\xi_3 \end{pmatrix}$$



C.-P. Yuan's talk @ MBI 2023

New polarization observables

Linear polarization/transversely polarized effects for NP searches

- Boosted top quark (hadronic mode), linear polarization of W boson
Zhite Yu, C.-P. Yuan, PRL 129 (2022) 11,11

- Linear polarization of photon @ ultraperipheral heavy ion collisions (UPCs)
Ding Yu Shao, Bin Yan, Shu-Run Yuan, Cheng Zhang, 2310.14153

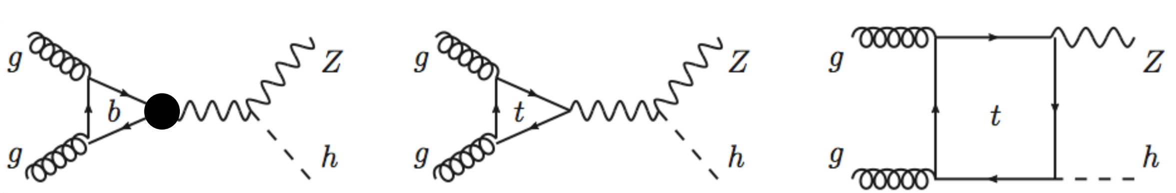
- Transversely polarized effects @ lepton collider
Xin-Kai Wen, Bin Yan, Zhite Yu, C.-P. Yuan, 2307.05236 (highlight paper in PRL)
Yan Hu, Yandong Liu, Xin-Kai Wen, Bin Yan, working in progress

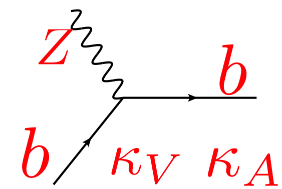
- Transversely polarized effects @ EIC
R. Boughezal et al, PRD 107 (2023) 7,075028
Hao-Lin Wang, Xin-Kai Wen, Hongxi Xing, Bin Yan, working in progress

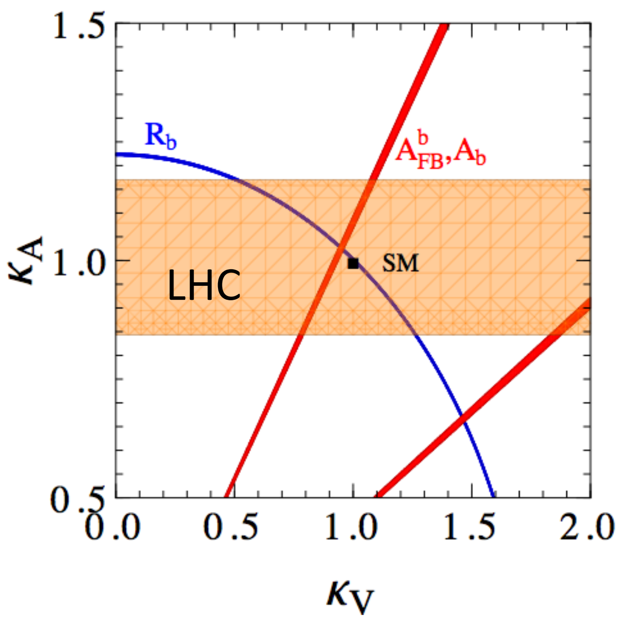
This new polarization observable would be important for probing the CP violation, and becoming popular

Electroweak properties for the SM

The precisely measurements for the SM Higgs production can also test the electroweak properties of the SM







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

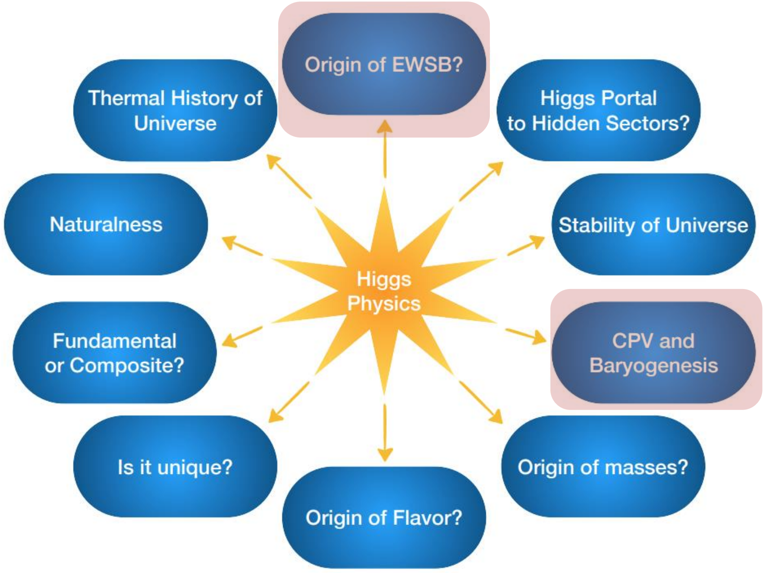
$$\mathcal{L} = \bar{b}\gamma_\mu(\kappa_V g_V - \kappa_A g_A \gamma_5) b Z_\mu$$

The degeneracy of the anomalous Zbb could be resolved by the LHC data

The other possible methods:
Bin Yan, C.-P. Yuan, Shu-Run Yuan, PRD 108 (2023) 5, 053001
F. Bishara, Zhuoni Qian, JHEP 10 (2023) 088
Hongxin Dong, Peng Sun, Bin Yan, C.-P. Yuan, PLB 829 (2022) 137076
Hai Tao Li, Bin Yan, C.-P. Yuan, PLB 833 (2022) 137300
Bin Yan, Zhite Yu, C.-P. Yuan, PLB 822 (2021) 136697

Summary

- The properties of the Higgs boson are closely related to many fundamental questions of particle physics



- Other interesting topics are not be covered: top quark physics, electroweak physics, jet physics,…

Thank you!