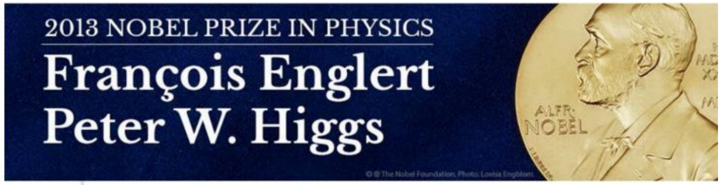
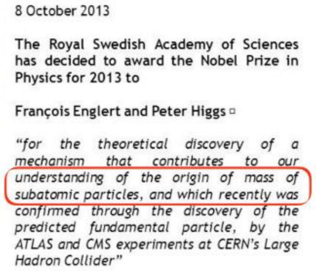
Higgs properties and new physics beyond the SM

Bin Yan
Institute of High Energy Physics

第五届粒子物理前沿研讨会
April 12-16, 2024

The Era of the Higgs Physics



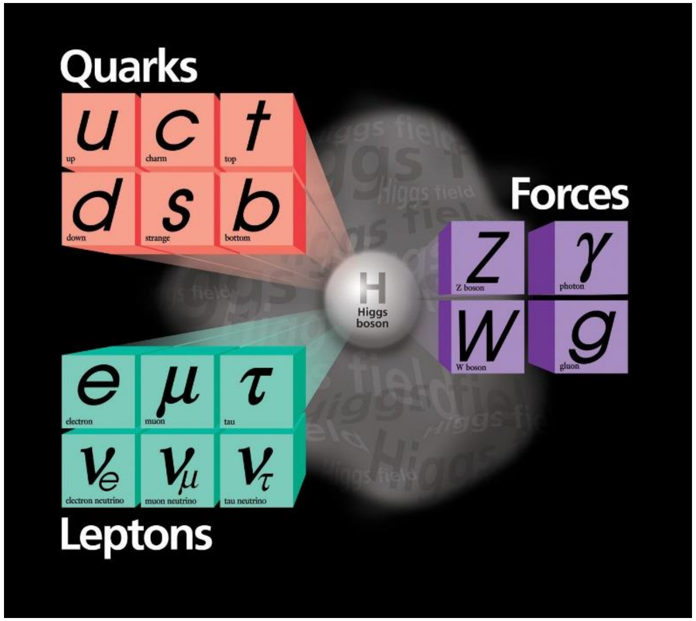


8 October 2013

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

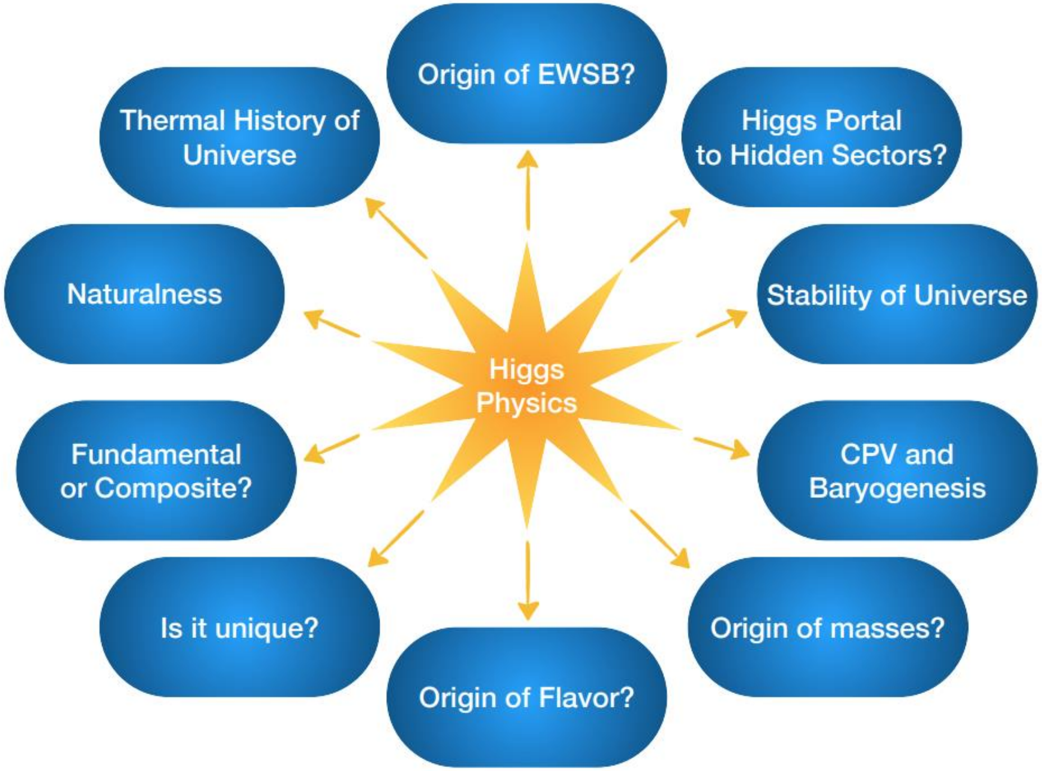
François Englert and Peter Higgs

"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 Physics

Origin of EWSB?

Higgs Portal to Hidden Sectors?

Stability of Universe

CPV and Baryogenesis

Origin of masses?

Origin of Flavor?

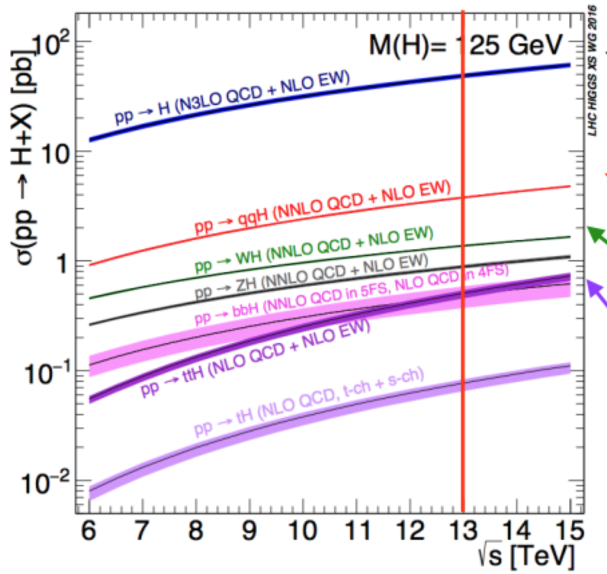
Is it unique?

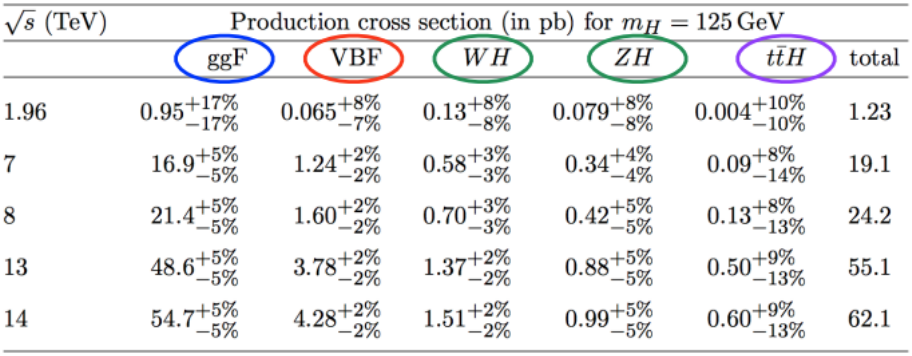
Fundamental or Composite?

Naturalness

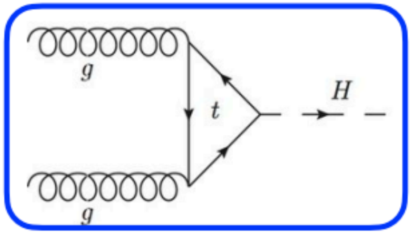
Thermal History of Universe

Higgs production @LHC

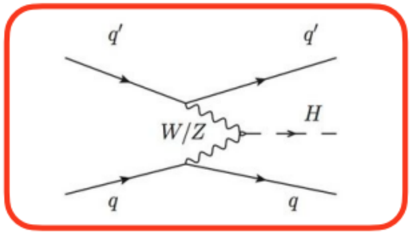




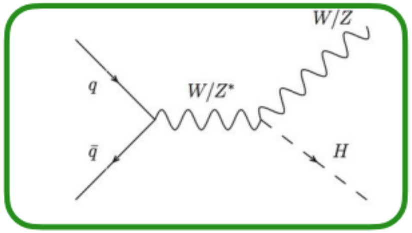
$\sqrt{s}$ (TeV)	Production cross section (in pb) for $m_H = 125\,\text{GeV}$					
	ggF	VBF	WH	ZH	$t\bar{t}H$	total
1.96	$0.95^{+17\%}_{-17\%}$	$0.065^{+8\%}_{-7\%}$	$0.13^{+8\%}_{-8\%}$	$0.079^{+8\%}_{-8\%}$	$0.004^{+10\%}_{-10\%}$	1.23
7	$16.9^{+5\%}_{-5\%}$	$1.24^{+2\%}_{-2\%}$	$0.58^{+3\%}_{-3\%}$	$0.34^{+4\%}_{-4\%}$	$0.09^{+8\%}_{-14\%}$	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



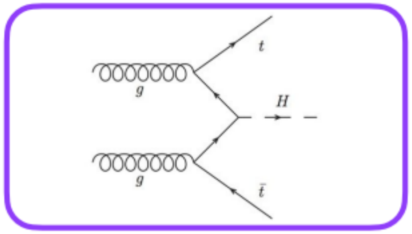
N³LO



N³LO



NNLO

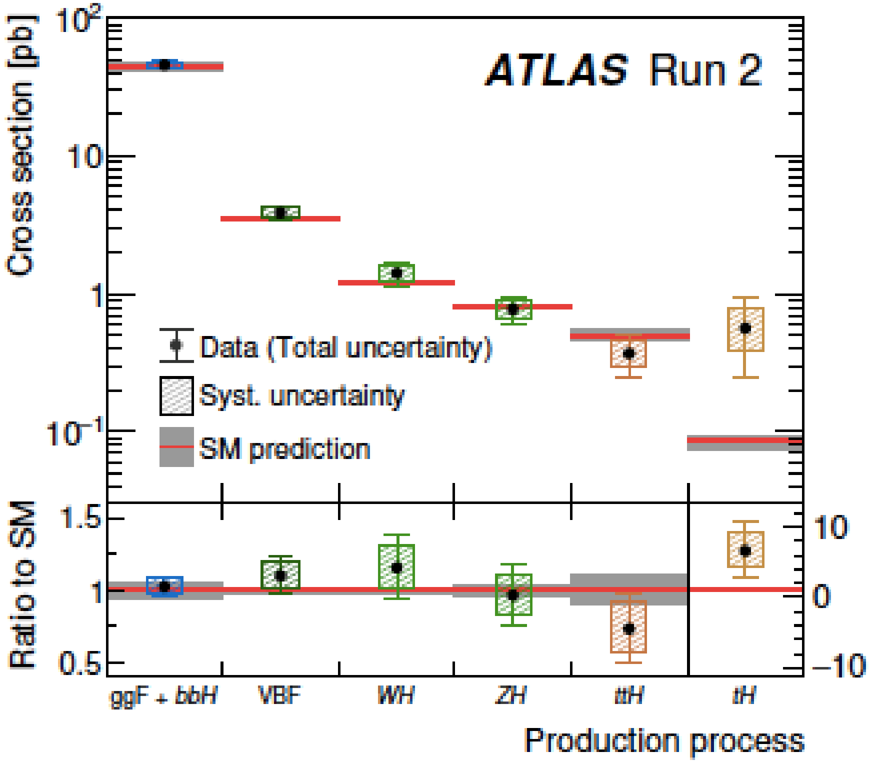


NLO + approx NNLO

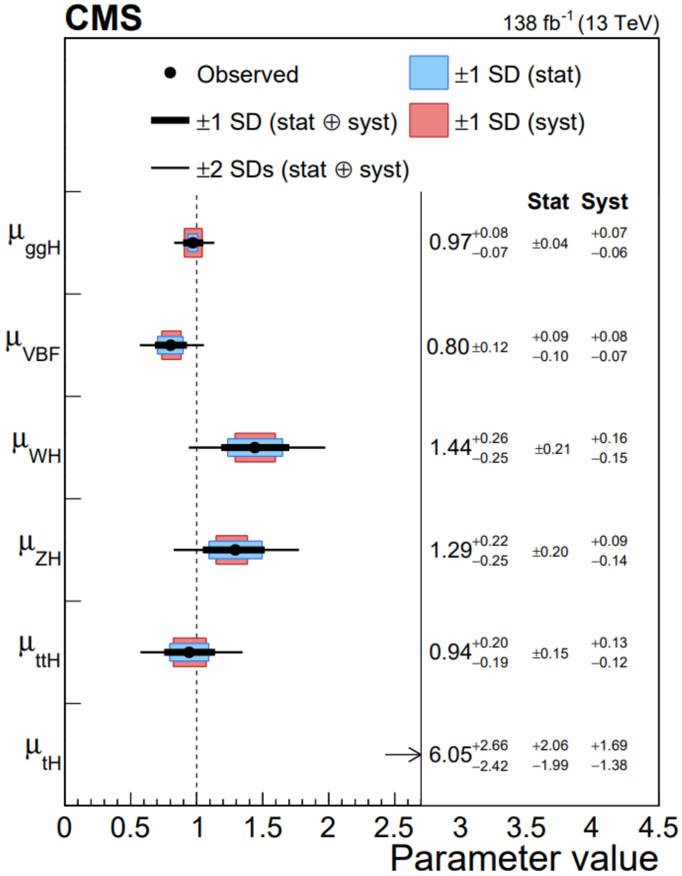
G. Zanderighi Higgs 2022

The measurements @ LHC

Nature 607 (2022)7917,52-59



Nature 607 (2022)7917,60-68



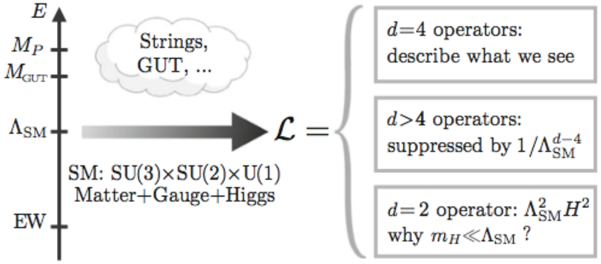
The data agrees with the SM prediction very well

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



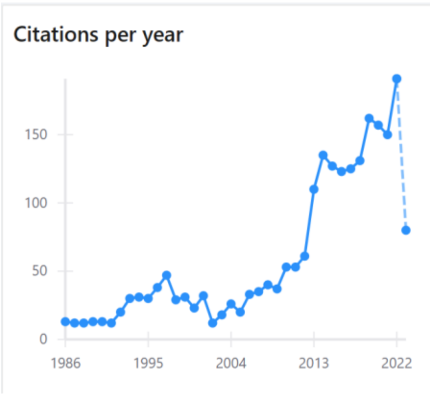
W. Buchuller, D. wyler 1986
B. Grzadkowski et al, 2010
L. Lehman, A. Marin, 2015
B. Henning et al, 2015
H-L. Li et al, 2020
Murphy, 2020

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

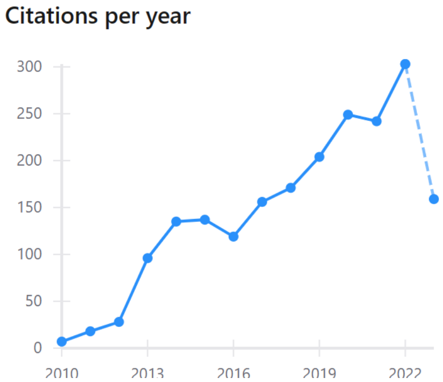
Linear realized EFT

Higgs is a fundamental particle
Weak interacting

W. Buchuller, D. wyler 1986



B. Grzadkowski et al, 2010

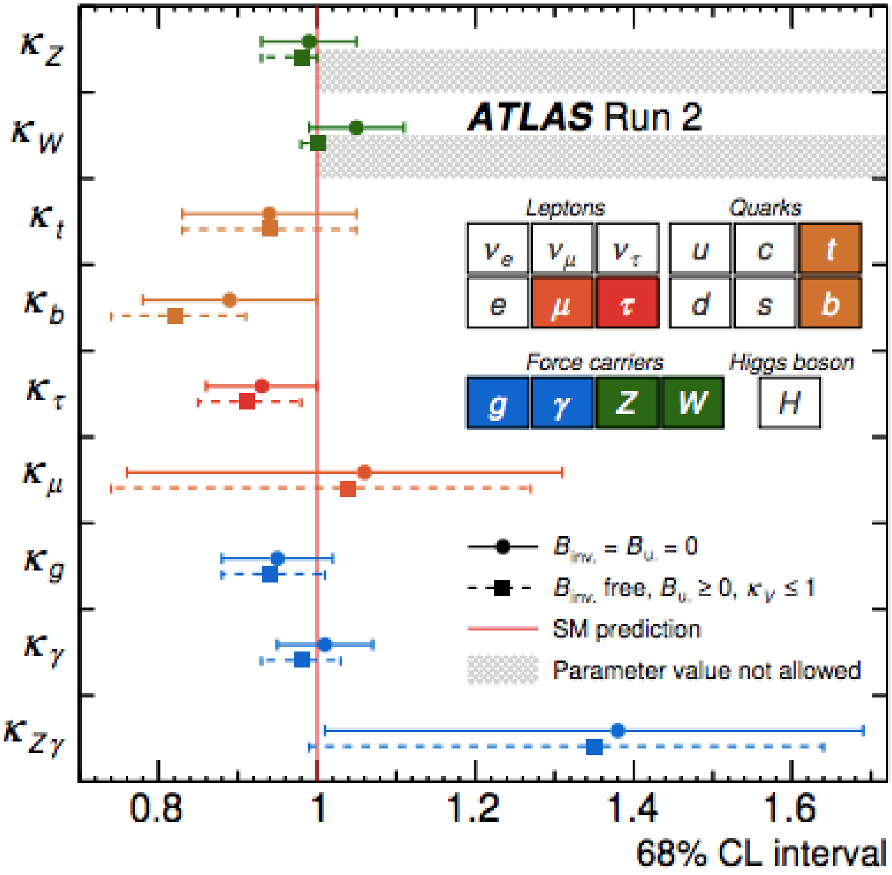


3. Higgs Effective Field Theory

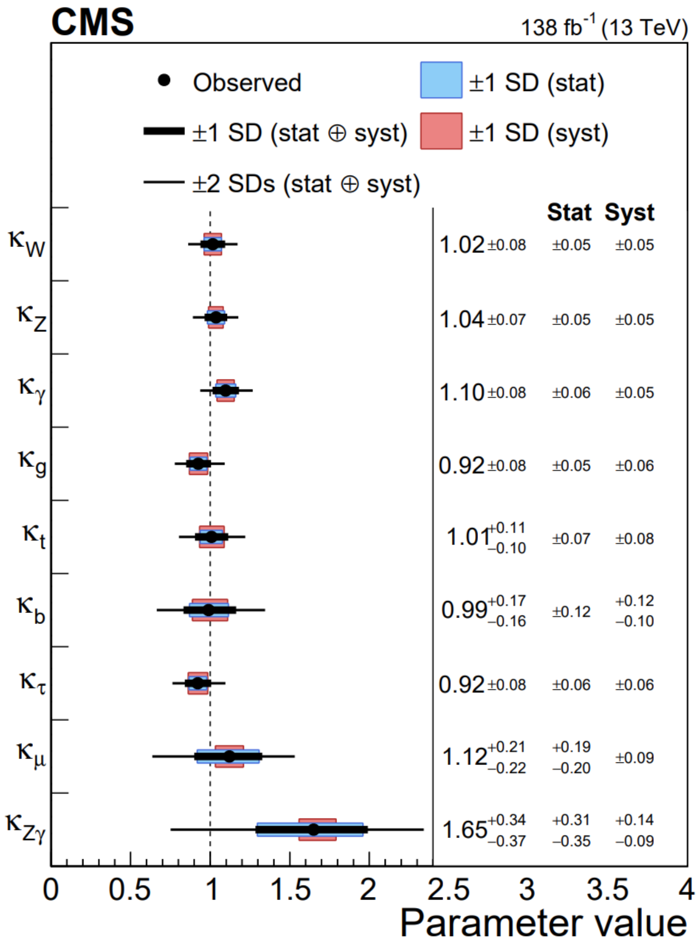
Callan, Coleman, Wess, Zumino, 1969
The electroweak chiral Lagrangian+light Higgs, A.C. Longhitano, 1980,….

Higgs couplings @LHC

Nature 607 (2022)7917,52-59



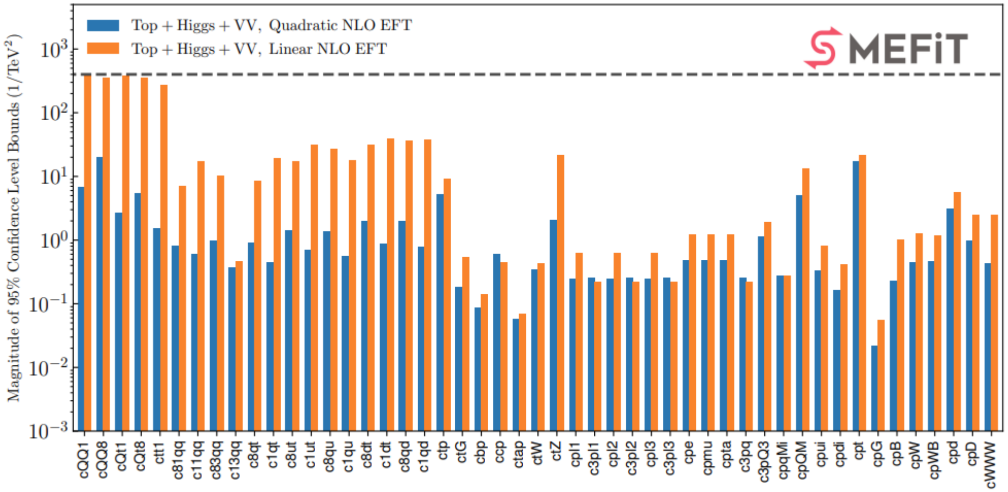
Nature 607 (2022)7917,60-68

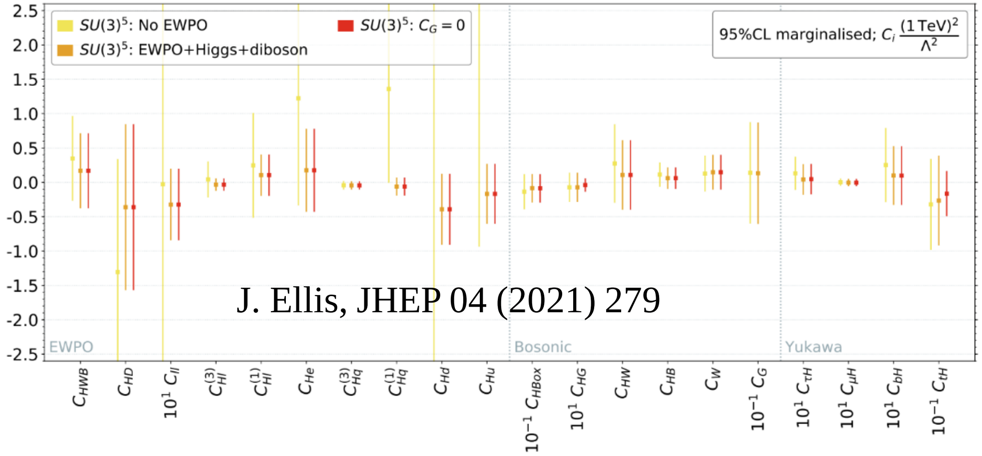


The data agrees with the SM prediction very well

Global Analysis @ SMEFT

SMEFiT Collaboration, JHEP 11 (2021) 089





J. Ellis, JHEP 04 (2021) 279

The SMEFT approach allows for the combination

◆ Higgs data

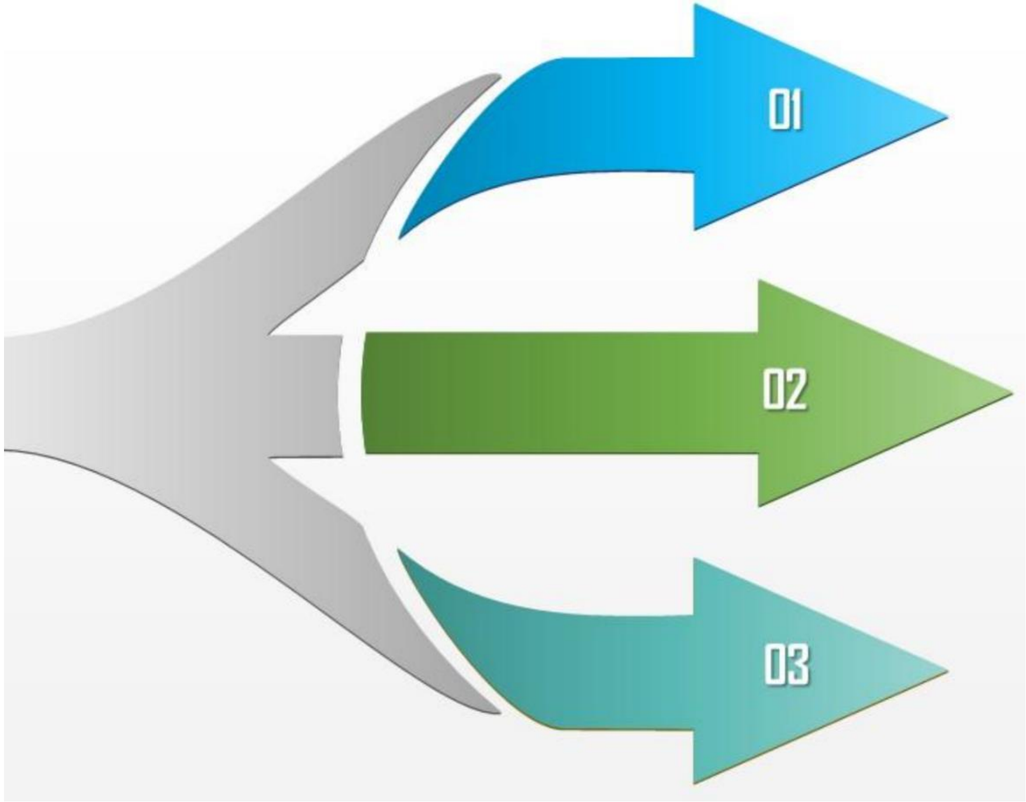
◆ Electroweak precision observables

◆ Diboson production

◆ Top quark Physics

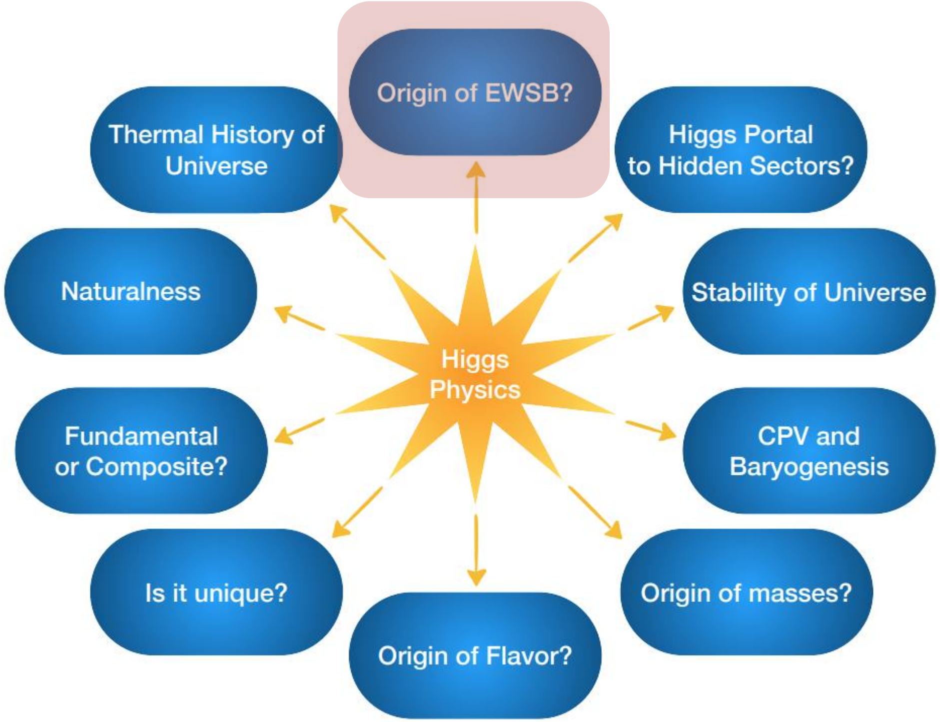
SMEFT is becoming one of the standard tool for the LHC experimental analysis

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

Testing the EWSB @ LHC



Origin of EWSB?

Thermal History of Universe

Higgs Portal to Hidden Sectors?

Naturalness

Stability of Universe

Higgs Physics

Fundamental or Composite?

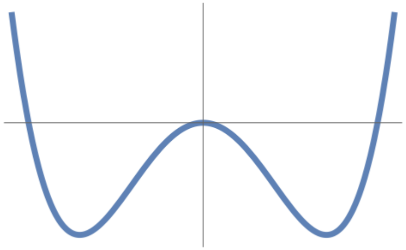
CPV and Baryogenesis

Is it unique?

Origin of masses?

Origin of Flavor?

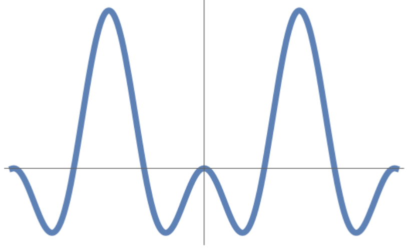
Landau-Ginzburg Higgs



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

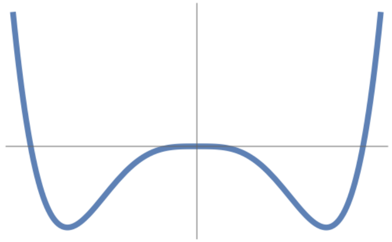
Agrawal, Saha, Xu, Yu, Yuan, 2019

Pseudo-Goldstone Higgs



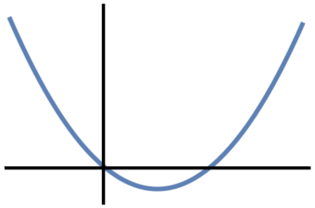
$$V(\phi) = a\sin^2(\phi/f) + b\sin^4(\phi/f)$$

Coleman Weinberg Higgs



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

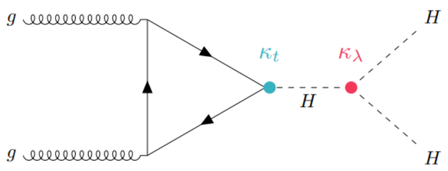
Tadpole-induced Higgs

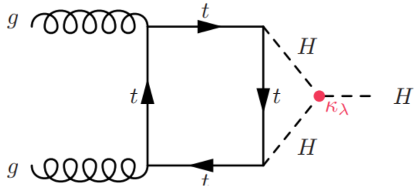


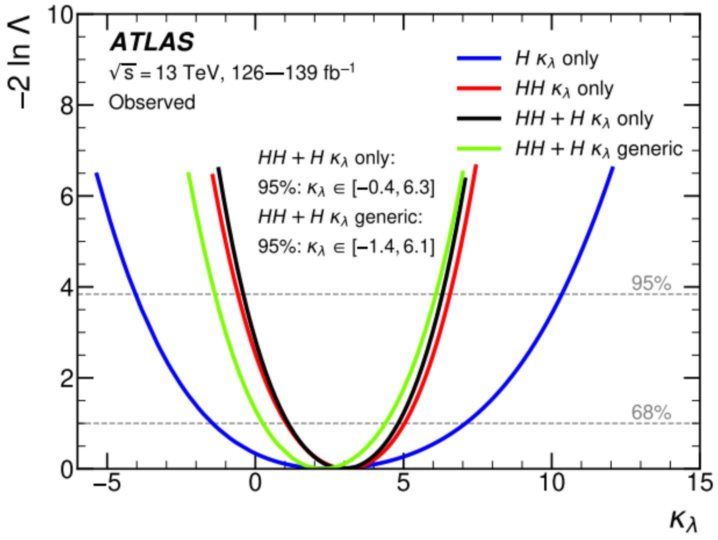
$$V(\phi) = -\mu^3\sqrt{\phi^\dagger\phi} + m^2\phi^\dagger\phi$$

Testing the EWSB @ LHC

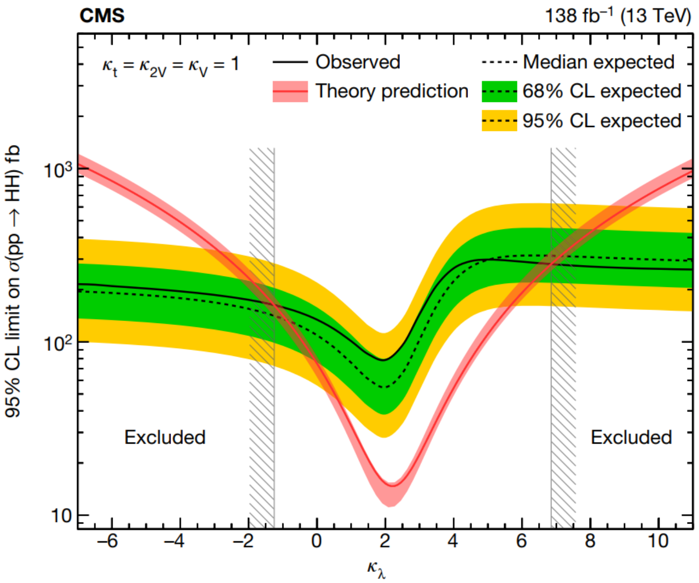
To determine the Higgs potential shape is challenge!







ATLAS, PRD108 (2023)5, 052003

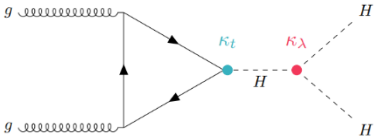


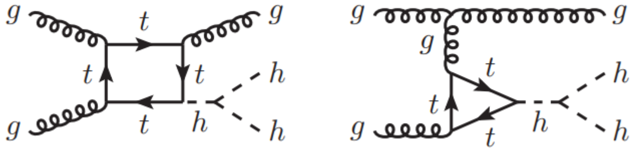
Nature 607 (2022) 60

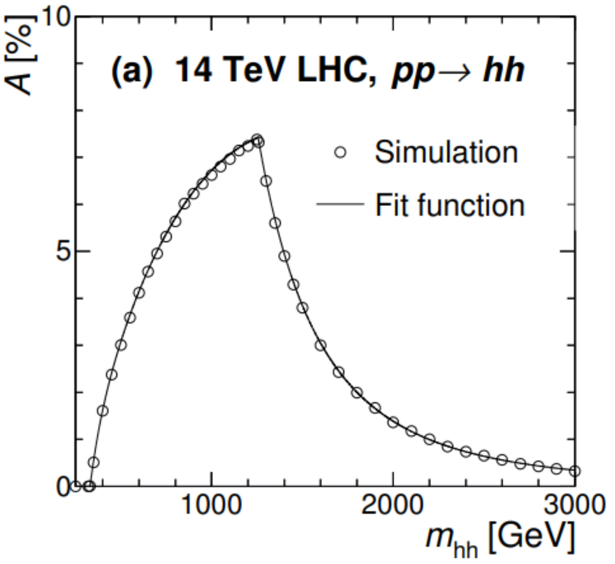
Testing the EWSB @ LHC

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

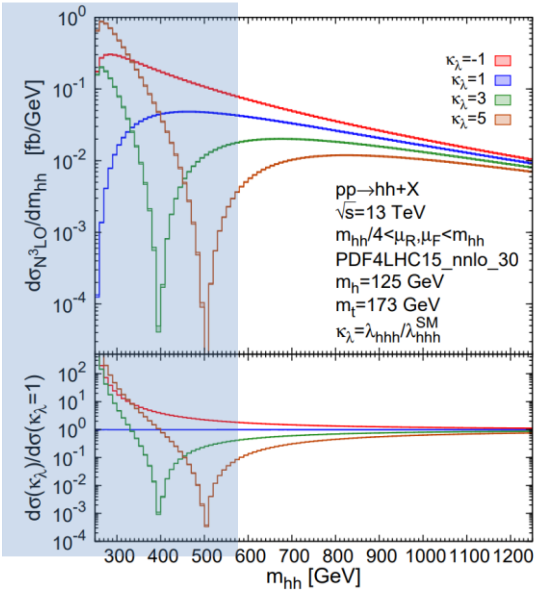
The low di-Higgs invariant mass region is more sensitive to the Higgs shape



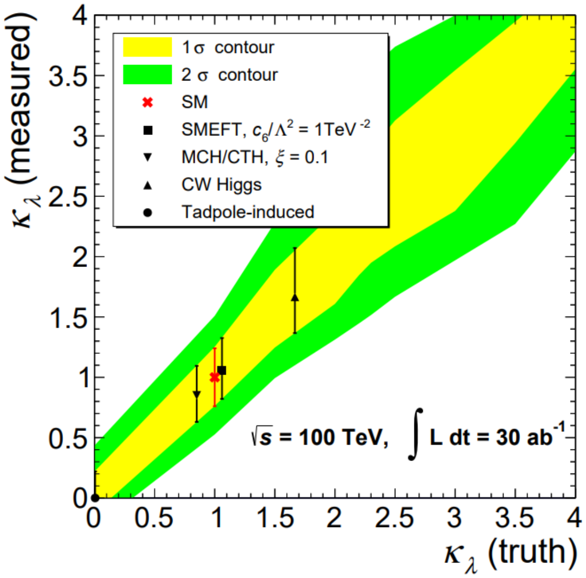




Q.-H. Cao, Bin Yan, D.-M. Zhang, H. Zhang, PLB 752 (2016) 285-290

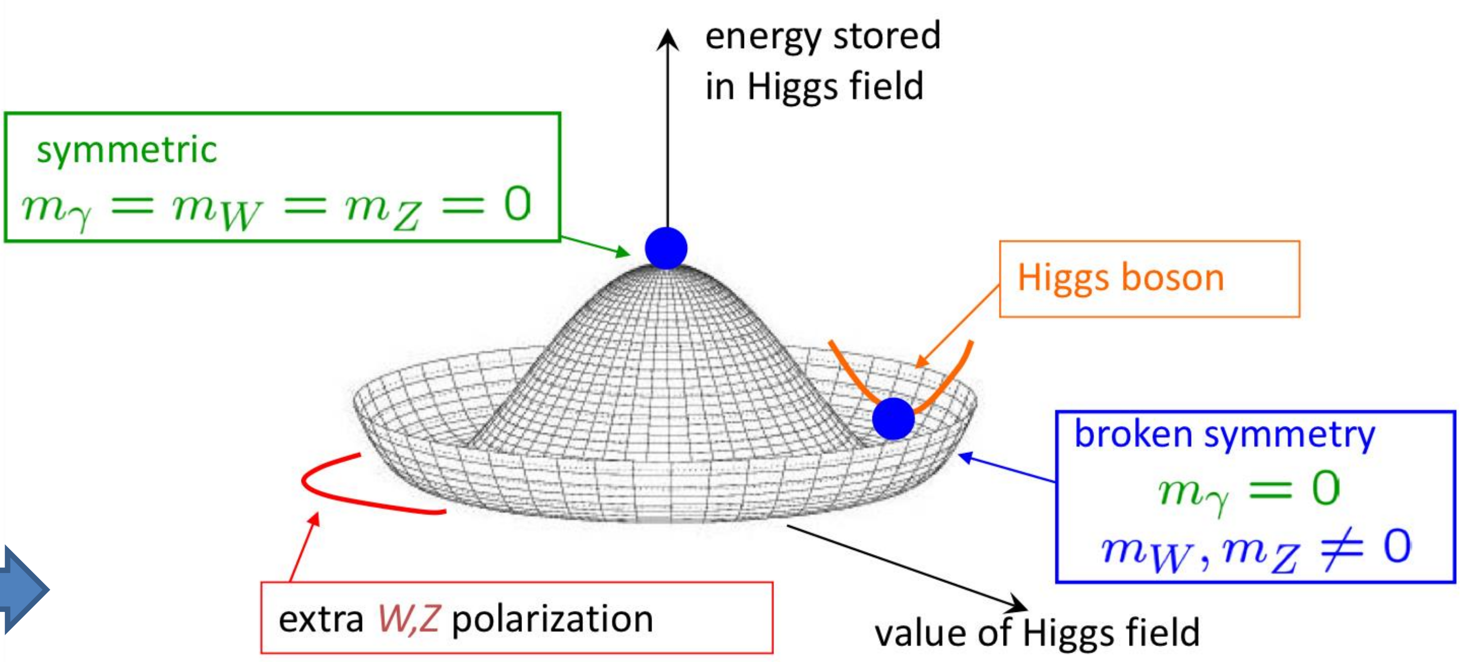


L. B. Chen, H. T. Li, H. S. Shao, J. Wang, PLB 803 (2020) 135292, JHEP 03 (2020) 072



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

Testing the EWSB @ LHC



energy stored
in Higgs field

symmetric
$m_\gamma = m_W = m_Z = 0$

Higgs boson

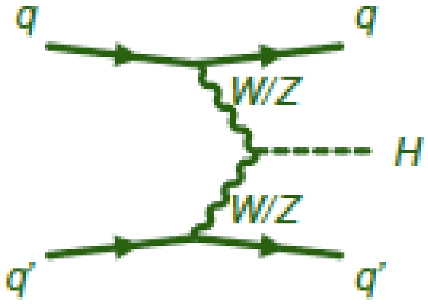
broken symmetry
$m_\gamma = 0$
$m_W, m_Z \neq 0$

extra *W,Z* polarization

value of Higgs field

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

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

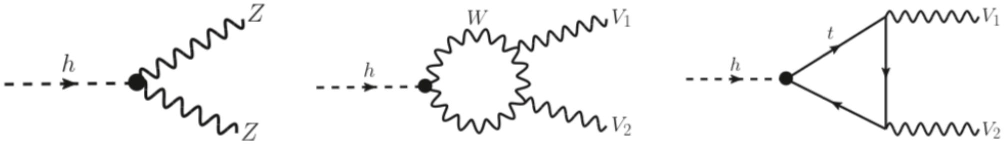


Higgs couplings and EWSB

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

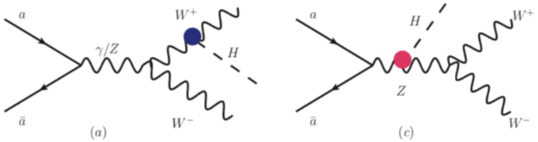
Y. Chen et al, PRL 2016

☐ Interference between tree and loop level in Higgs decay

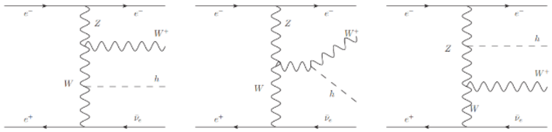


☐ Lepton Colliders

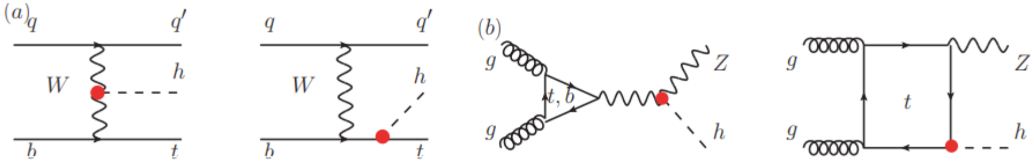
C.W Chiang, X. G. He and G. Li, JHEP08(2018) 126



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



☐ th and Zh production

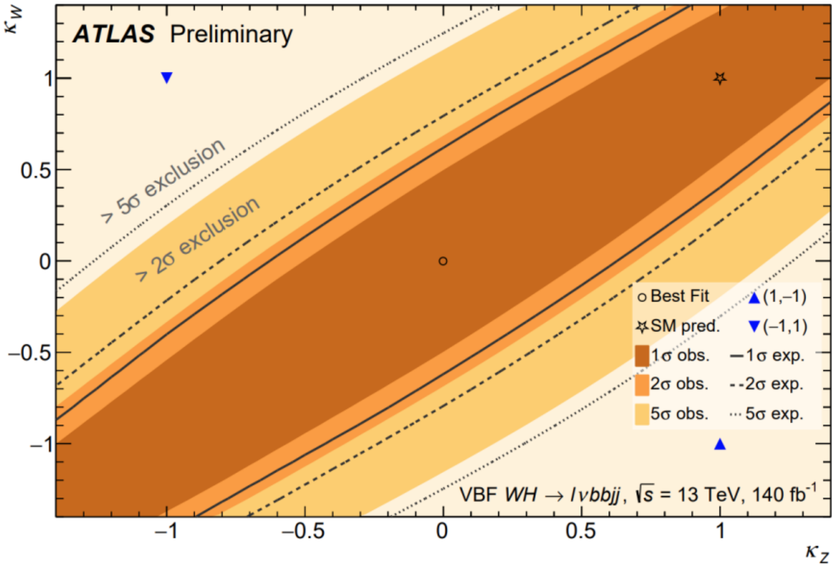


The data favors the same sign

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

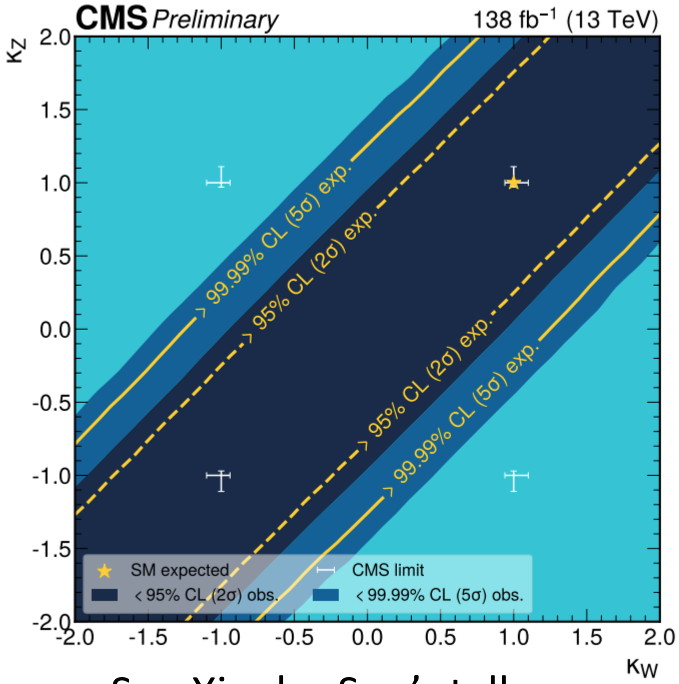
Higgs couplings and EWSB

ATLAS-CONF-2023-057

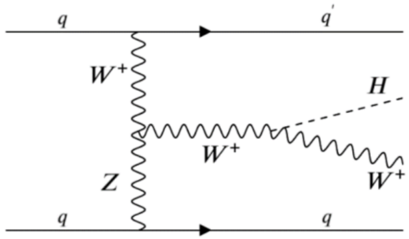


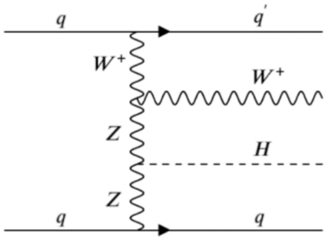
See Yusheng Wu’s talk

CMS-PAS-HIG-23-007



See Xiaohu Sun’s talk

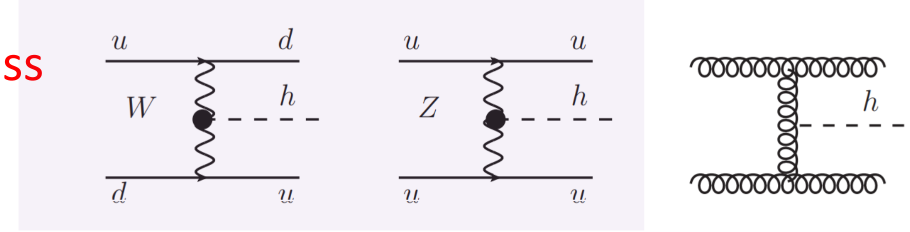




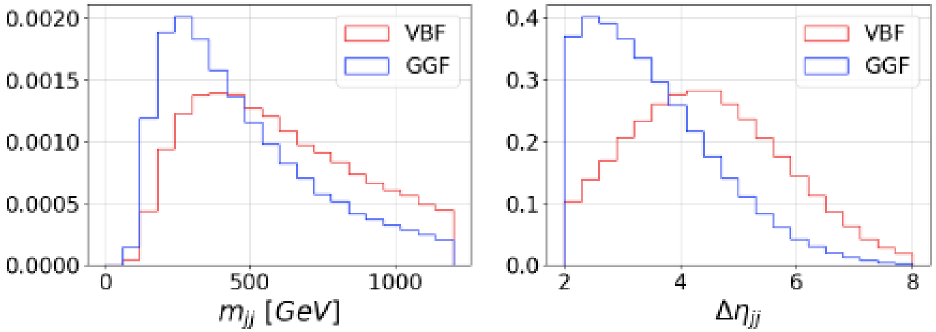
The magnitude of the Higgs gauge couplings would be the key task for testing EWSB

Higgs production mechanisms

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

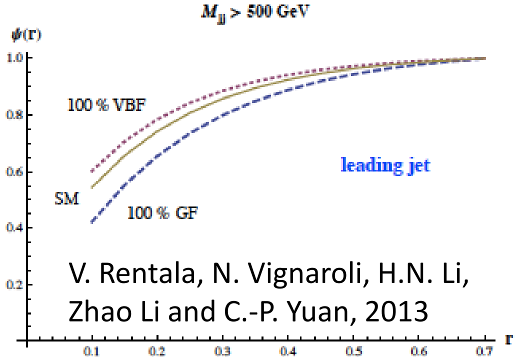


- ➢ The rapidity gap and the invariant mass of the two jets



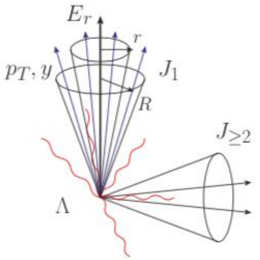
V.D. Bargeer, K.m.Cheung. T. Han, J. Ohnemus and D. Zeppenfeld, 1991
N. Kauer, T. Plehn, D. L. Rainwater and D. Zeppenfeld, 2001
……

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

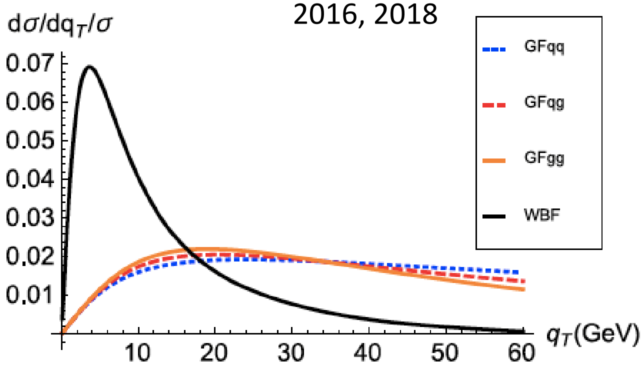


V. Rentala, N. Vignaroli, H.N. Li, Zhao Li and C.-P. Yuan, 2013

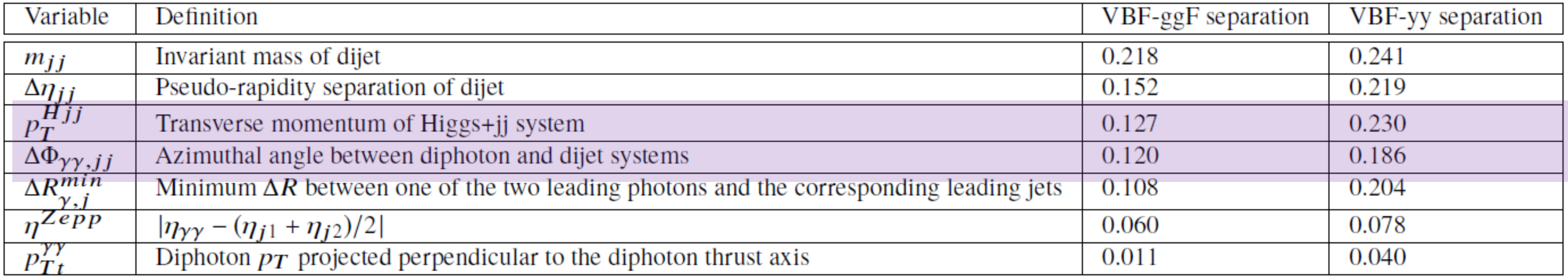
$$\Psi_J(r) = \frac{\sum_{i,d_{i,\hat{n}}<r} E_T^i}{\sum_{i,d_{i,\hat{n}}<R} E_T^i}$$



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



Higgs production mechanisms

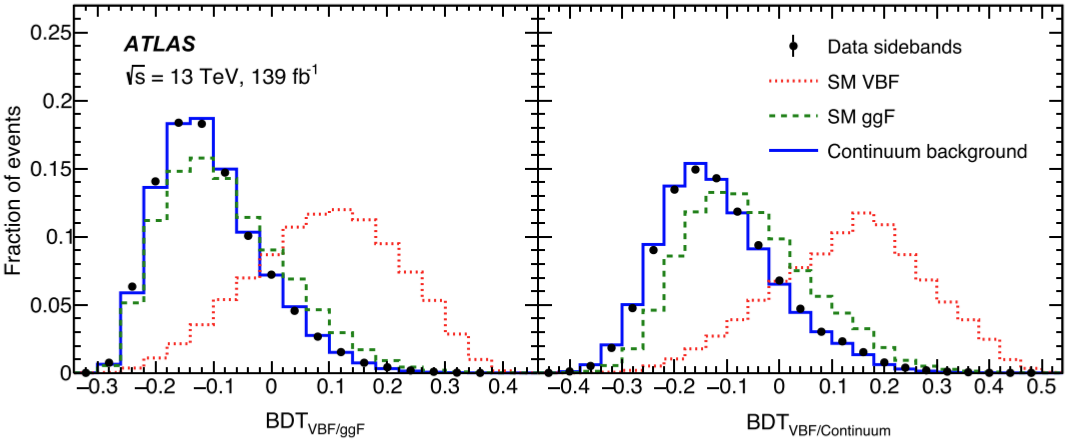


Variable	Definition	VBF-ggF separation	VBF-yy separation
m_{jj}	Invariant mass of dijet	0.218	0.241
$\Delta\eta_{jj}$	Pseudo-rapidity separation of dijet	0.152	0.219
p_T^{Hjj}	Transverse momentum of Higgs+jj system	0.127	0.230
$\Delta\Phi_{\gamma\gamma,jj}$	Azimuthal angle between diphoton and dijet systems	0.120	0.186
$\Delta R^{min}_{\gamma,j}$	Minimum ΔR between one of the two leading photons and the corresponding leading jets	0.108	0.204
η^{Zepp}	$\lvert\eta_{\gamma\gamma} - (\eta_{j1} + \eta_{j2})/2\rvert$	0.060	0.078
$p_{Tt}^{\gamma\gamma}$	Diphoton p_T projected perpendicular to the diphoton thrust axis	0.011	0.040

Table 7: Variables used for VBF categorization and their separation power.

Soft gluon radiation effects: TMD effects

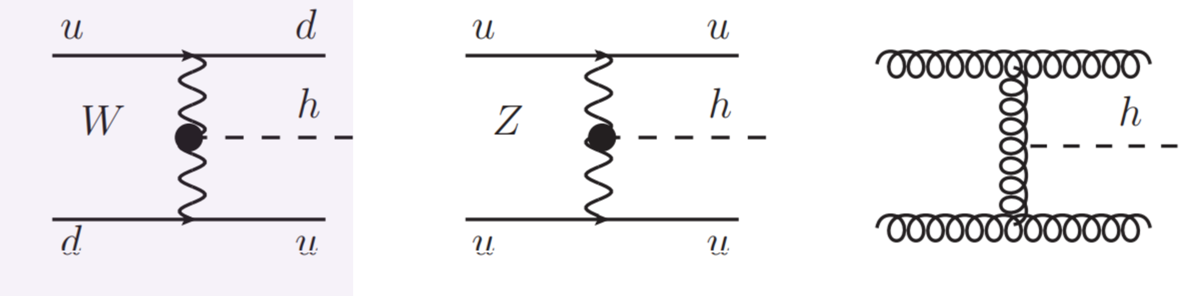
ATLAS, Phys.Rev.Lett. 131 (2023) 6, 061802



The VBF Higgs production can be well seperated from the GGF process

Higgs production mechanisms

Discriminating W-boson fusion, Z-boson fusion and gluon fusion Higgs production

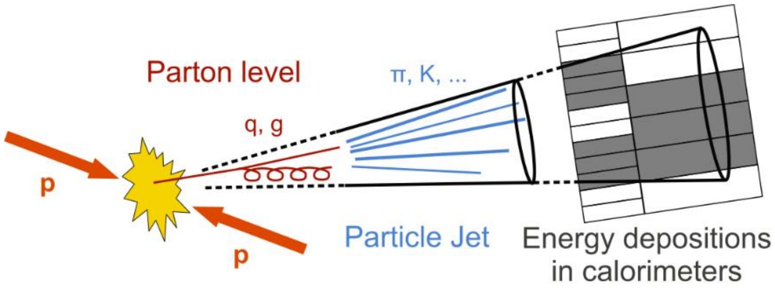


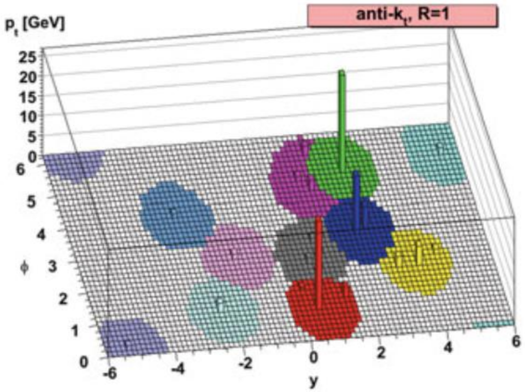
H. T. Li, Bin Yan, C.-P. Yuan, PRL 131 (2023) 4, 041802

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

The key observable: Jet Charge
W: opposite sign for the two jet charges
Z: same or opposite sign for the two jet charges
G: the sign of the jet charge is arbitrary

Jet charge definition





Transverse-momentum-weighting scheme:

$$Q_J = \frac{1}{(p_T^j)^\kappa} \sum_{i \in jet} Q_i (p_T^i)^\kappa, \ \kappa > 0$$

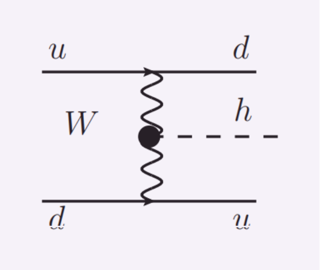
R.D. Field and R.P. Feynman, NPB136,1(1978)

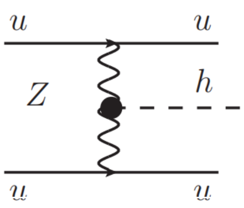
κ: To regulate the sensitivity of the soft gluon radiation

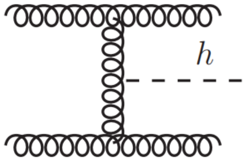
➢ SCET calculation	D. Krohn et al, PRL, 2013, W.J.Waalewijn, PRD, 2012
➢ Quark/gluon jet discrimination	K.Fraser and M.D. Schwartz, JHEP, 2018, Zhong-Bo Kang, Xiaohui Liu, et al, PRD, 2021
➢ Nuclear medium effects	H. T. Li and I. Vitev, PRD, 2020, PRL, 2021
➢ Quark flavor structure	Zhong-Bo Kang, Xiaohui Liu, et al, PRD, 2021, + Ding Yu Shao,PRL, 2020
➢ Non-perturbative model	Zhong-Bo Kang et al, PRL, 2023
➢ Electroweak and Higgs physics	H. T. Li, Bin Yan and C.-P. Yuan, PLB 2022, PRL 2023 Xiao-Rui Wang, Bin Yan, PRD 2023 H. Cui, M. Zhao, Y. Wang, H. Liang, Manqi Ruan, 2023

Higgs coupings @ VBF

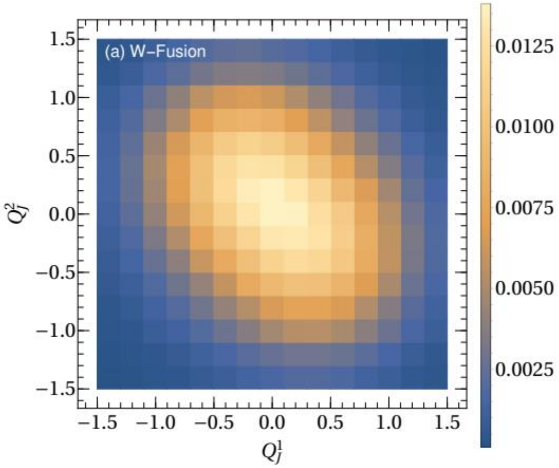
The key observable: Jet Charge



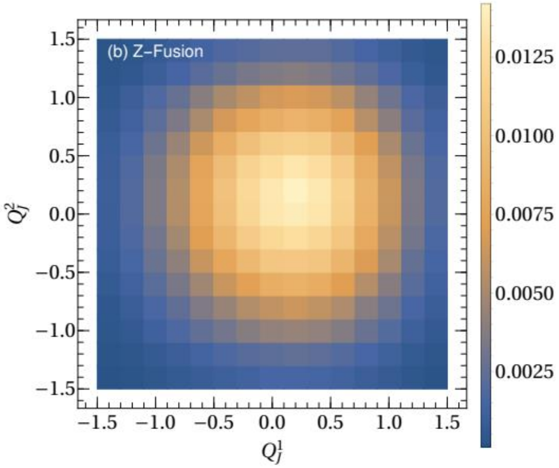




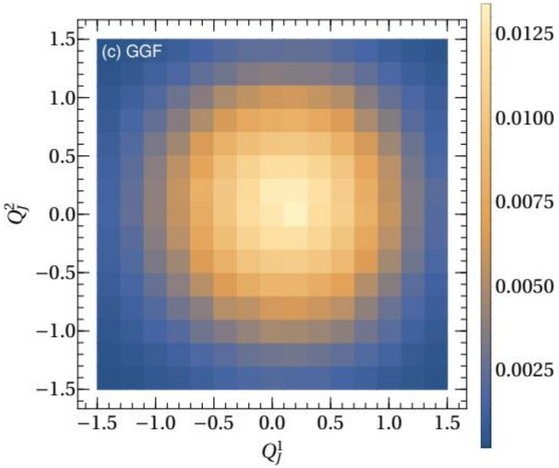
H. T. Li, Bin Yan, C.-P. Yuan,
PRL 131 (2023) 4, 041802



opposite sign for the two jet charges



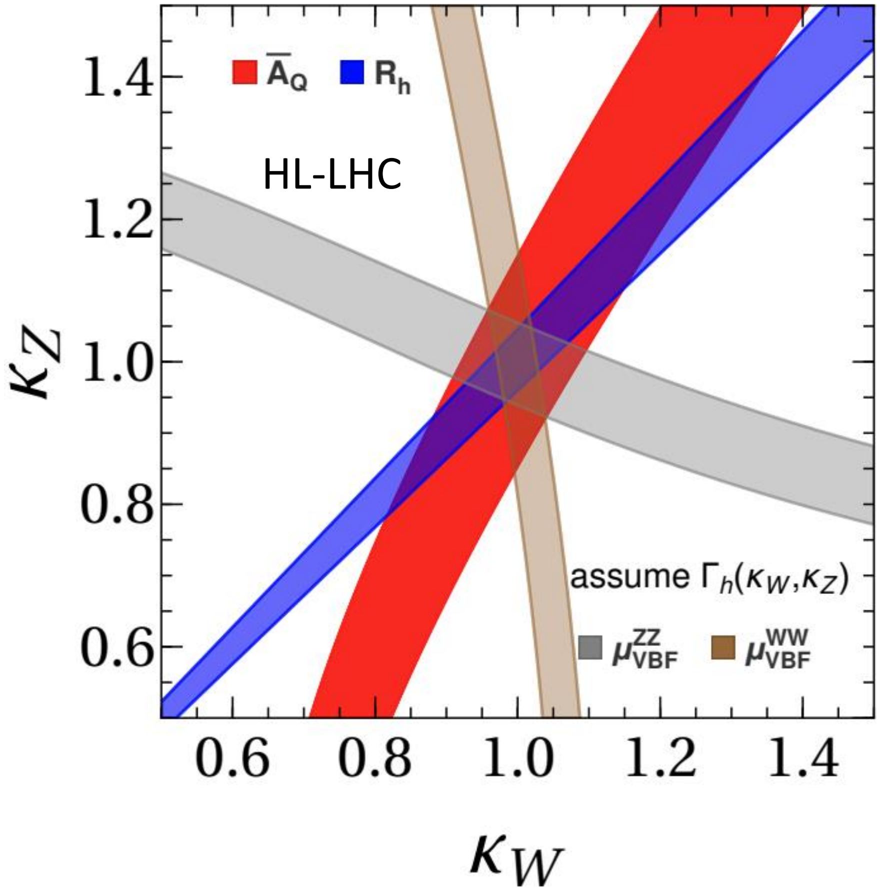
same or opposite sign



the sign of the jet charge is arbitrary

Higgs couplings @ VBF

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



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

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

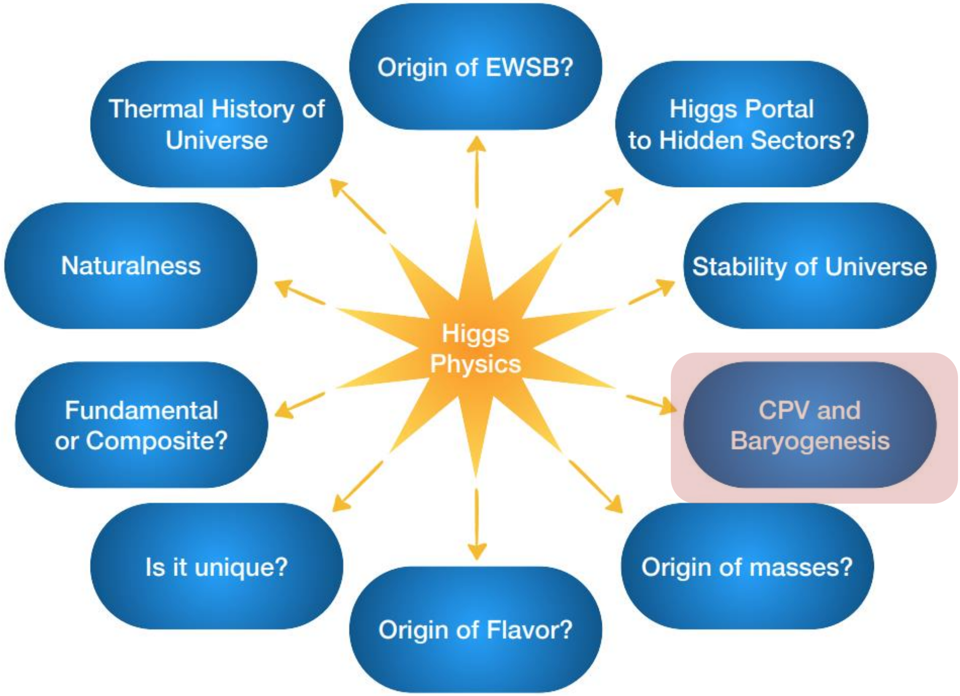
$$R_h = \frac{\mu(gg \to h \to WW^*)}{\mu(gg \to h \to ZZ^*)} = \frac{\kappa_W^2}{\kappa_Z^2}$$

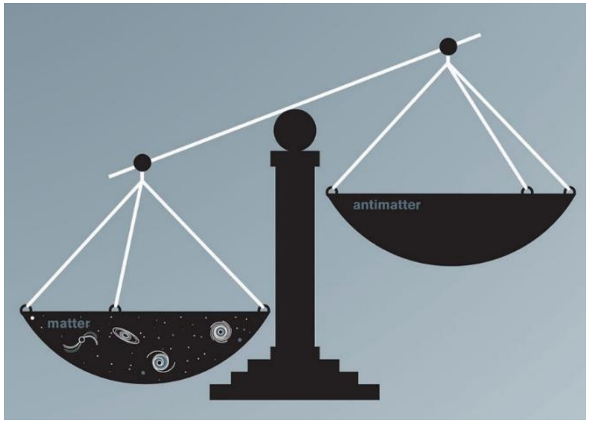
$$\kappa_V = \frac{g_{hVV}}{g_{hVV}^{\text{SM}}}$$

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)

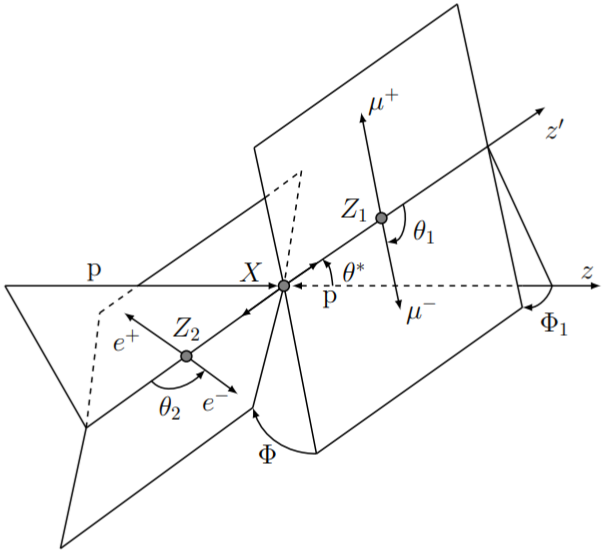
- B violation
- C & CP violations
- Departure from the equilibrium

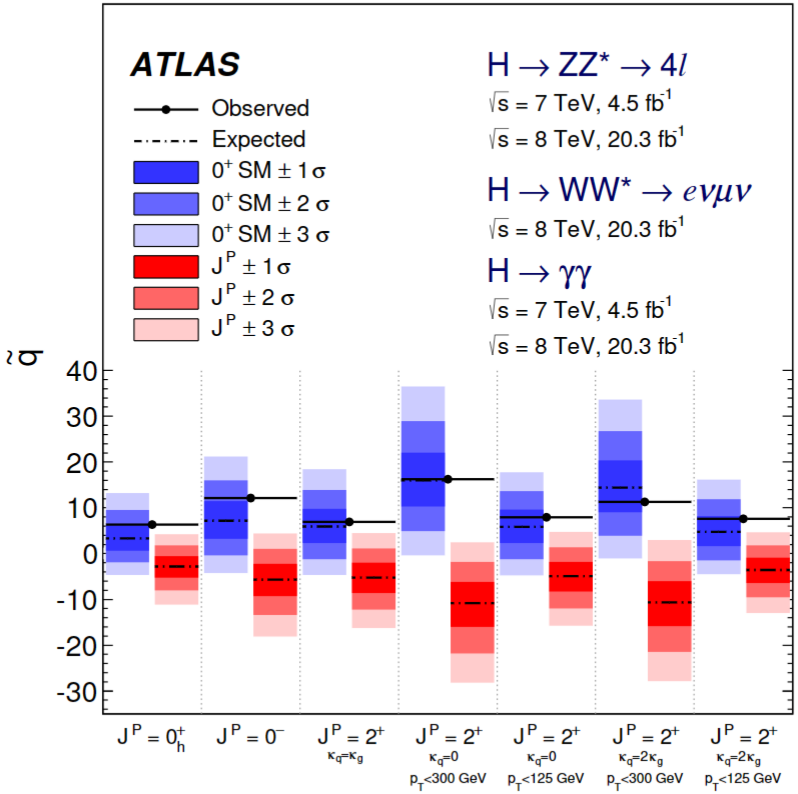
Higgs CP violation

PDG 2022

Higgs boson CP property:

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



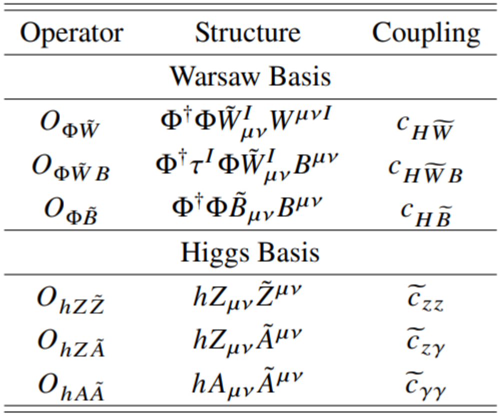


- ➢ A purely CP-odd Higgs has been excluded
- ➢ A CP-mixture Higgs boson is still possible

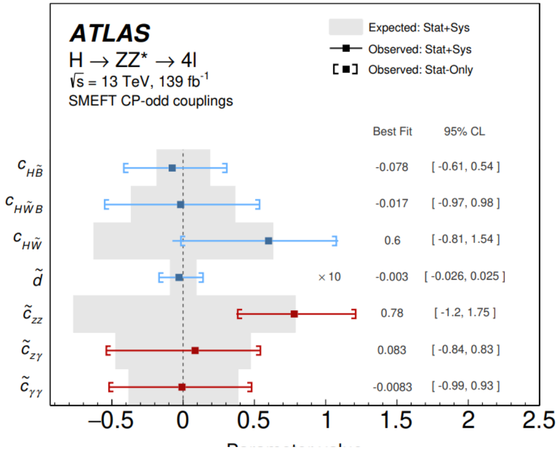
Higgs CP violation

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

ATLAS,2304.09612



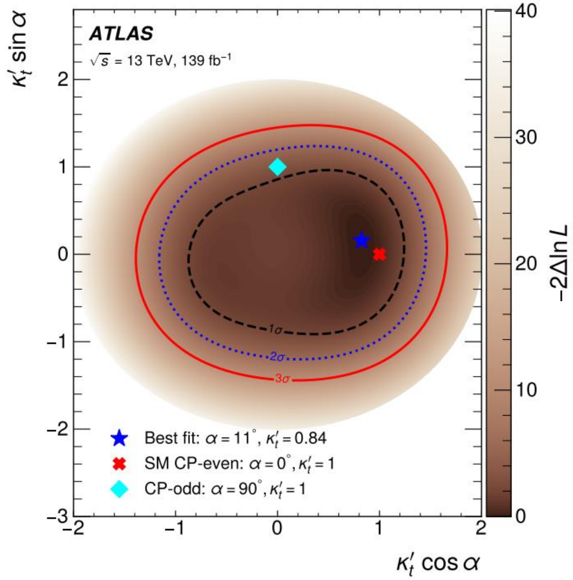
Operator	Structure	Coupling
	Warsaw Basis	
$O_{\Phi\tilde{W}}$	$\Phi^\dagger\Phi\tilde{W}^I_{\mu\nu}W^{\mu\nu I}$	$c_{H\widetilde{W}}$
$O_{\Phi\tilde{W}B}$	$\Phi^\dagger\tau^I\Phi\tilde{W}^I_{\mu\nu}B^{\mu\nu}$	$c_{H\widetilde{W}B}$
$O_{\Phi\tilde{B}}$	$\Phi^\dagger\Phi\tilde{B}_{\mu\nu}B^{\mu\nu}$	$c_{H\widetilde{B}}$
	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

ATLAS：2303.05974
CMS：2208.02686

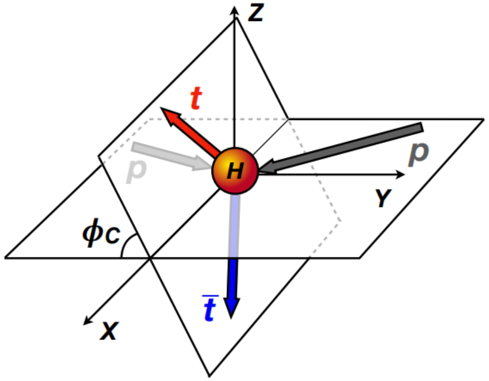
Gunion, He, PRL. 76, 4468 (1996)
Boudjema, Godbole, Guadagnolo, Mohan, PRD 92, 015019 (2015)
Mileo, Kiers, Szynkman, Crane, Gegner, JHEP 07, 056 (2016)
Gritsan, Rntsch, Schulze, Xiao, PRD 94, 055023 (2016)
S. Amor Dos Santos et al, PRD 96, 013004 (2017)
Kobakhidze, Liu, Wu, Yue, PRD 95 (2017) 1, 015016
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
…

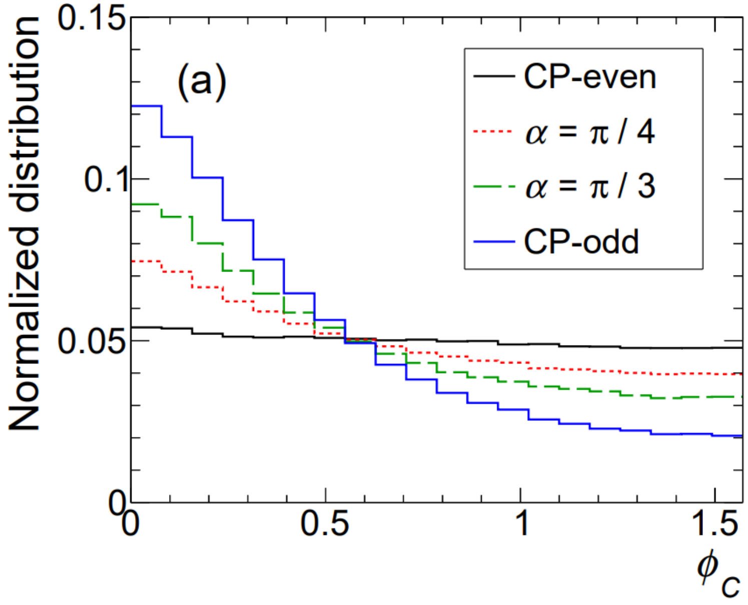


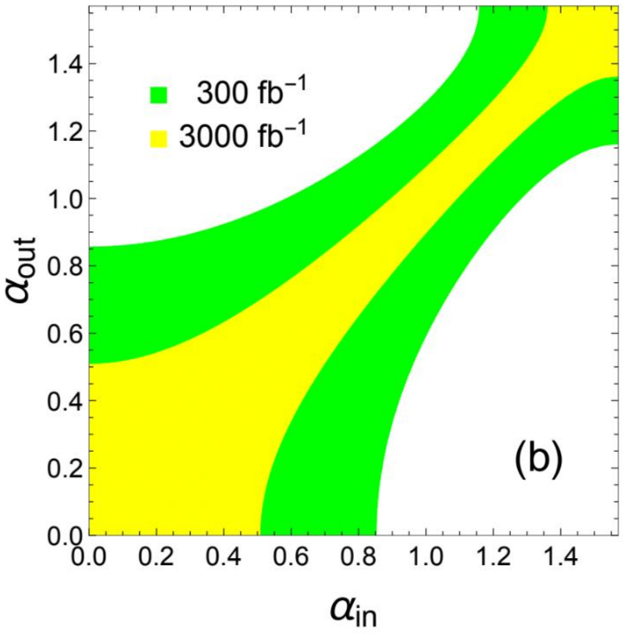
Higgs CP violation

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

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





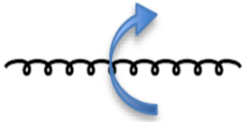


Q.-H. Cao, K.-P. Xie, H. Zhang , R. Zhang,CPC45 (2021)2,023117

New polarization observables

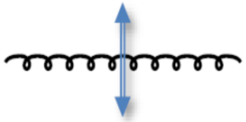
❑ Linear polarization vs. helicity/circular polarization

helicity pol.



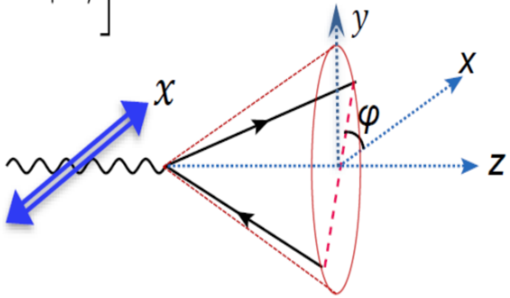
$|\pm 1\rangle$

linear pol.



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

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



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

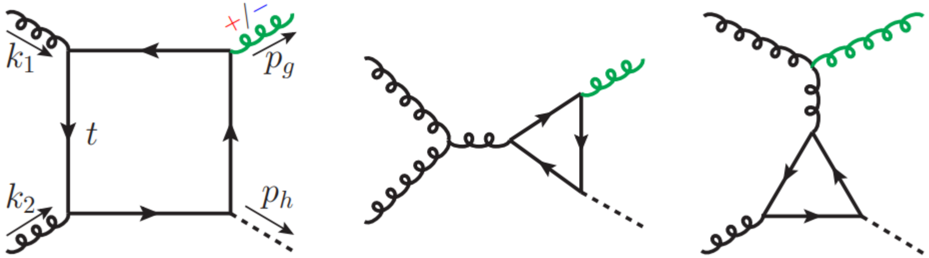
CP odd

Useful probes of new physics

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

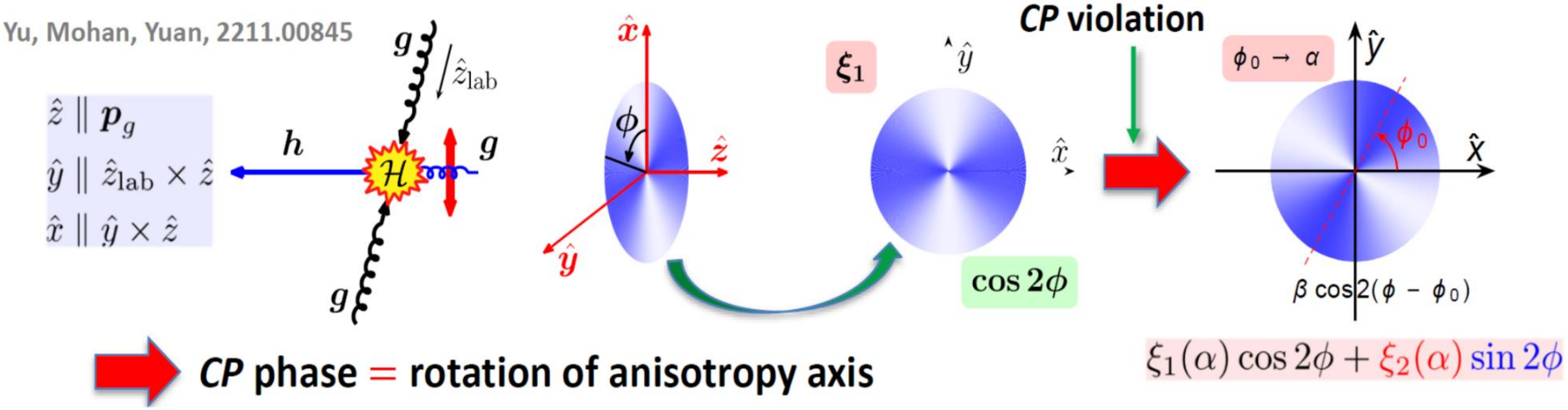
New polarization observables

Linear polarization of gluon



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

Yu, Mohan, Yuan, 2211.00845



CP phase = rotation of anisotropy axis

$\xi_1(\alpha)\cos 2\phi + \xi_2(\alpha)\sin 2\phi$

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, accepted by Science China Physics, Mechanics & Astronomy

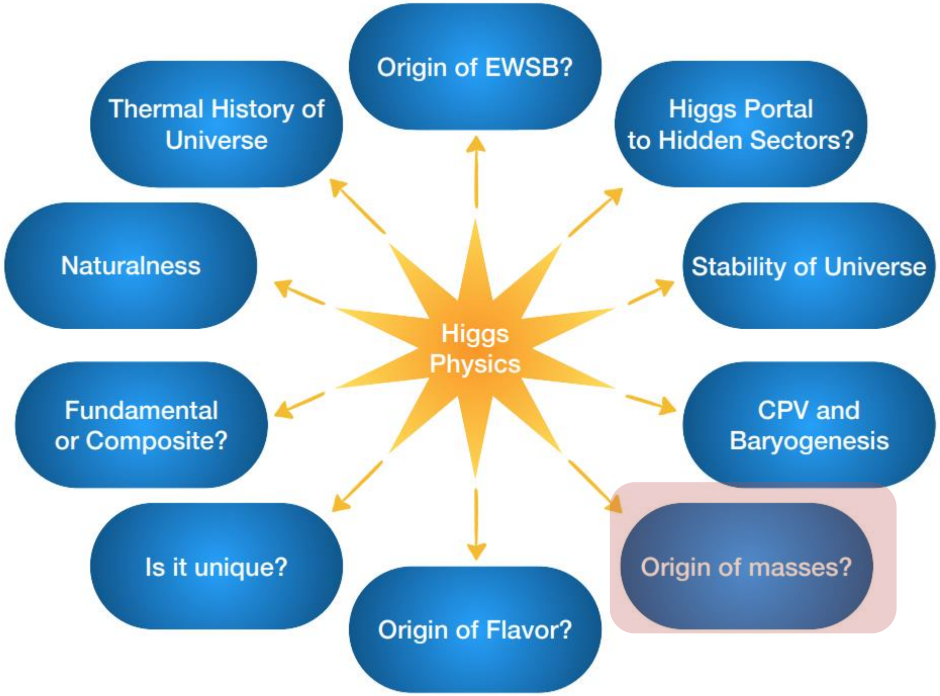
☐ Transversely polarized effects @ lepton collider
Xin-Kai Wen, Bin Yan, Zhite Yu, C.-P. Yuan, PRL 131 (2023) 241801

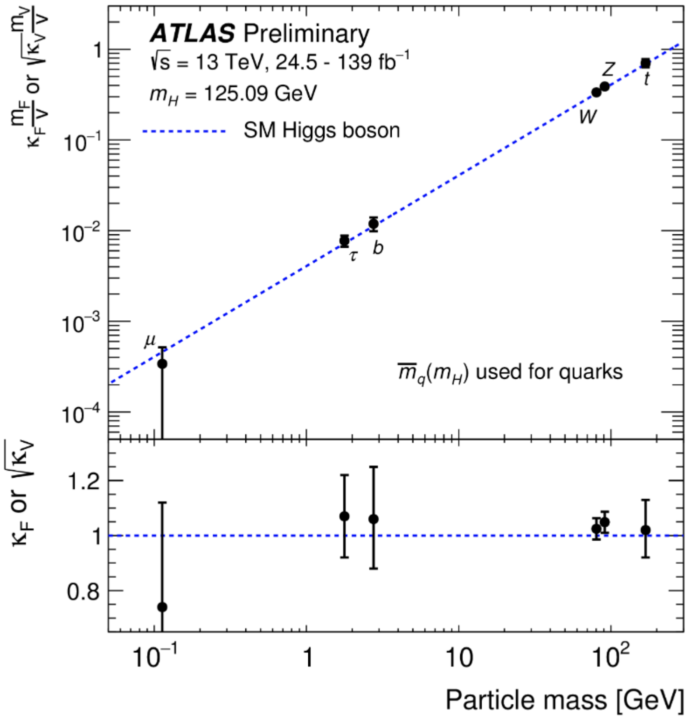
☐ Transversely polarized effects @ EIC
R. Boughezal et al, PRD 107 (2023) 7,075028
Hao-Lin Wang, Xin-Kai Wen, Hongxi Xing, Bin Yan, 2401.08419, Accepted by PRD

☐ Lam-Tung relation of Drell-Yan process
Xu Li, Bin Yan, C.-P. Yuan, 2404.xxxxx

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

Higgs Yukawa couplings





All fundamental particles get their mass from Higgs boson vev

How about light quarks?

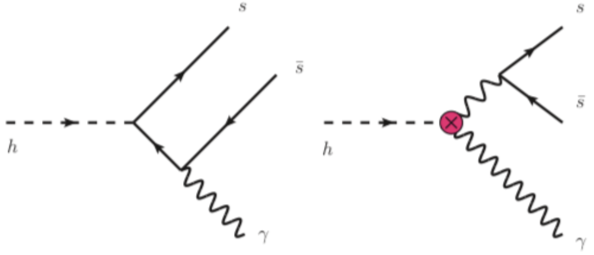
Does Higgs mechanism still work?

Light quark Yukawa couplings@LHC

A. Rare decay: $h \to J/\Psi\gamma \ (\phi\gamma, \rho\gamma, \omega\gamma)$

G. T. Bodwin, F. Petriello, S. Stoynev, M. Velasco, PRD88 (2013) 5, 053003
A. L. Kagan, G. Perez, F. Petriello, Y. Soreq, S. Stoynev, PRL114 (2015) 10,101802

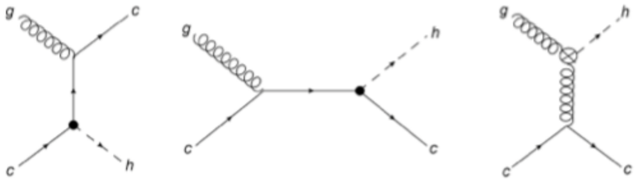
e.g. 14 TeV HL-LHC $y_s/y_b < 0.39 \quad y_c/y_c^{\rm SM} < 220$



B. Higgs+charm production

I. Brivio, F. Goertz, G. Isidori, PRL115 (2015)21,211801

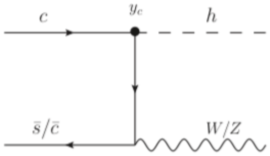
e.g. 14 TeV HL-LHC $y_c/y_c^{\rm SM} < 2.5$



C. Higgs data global analysis:

G. Perez, Y. Soreq, E. Stamou, K. Tobioka, PRD92(2015)3, 033016, PRD93(2016)1,013001
Y. Zhou, PRD93(2016) 1,013019

e.g. 14 TeV HL-LHC $y_c/y_c^{\rm SM} < 6.2$

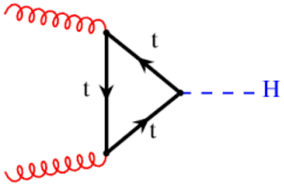


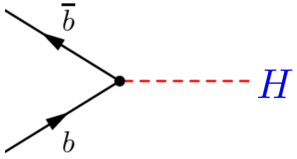
D. Higgs p_T analysis:

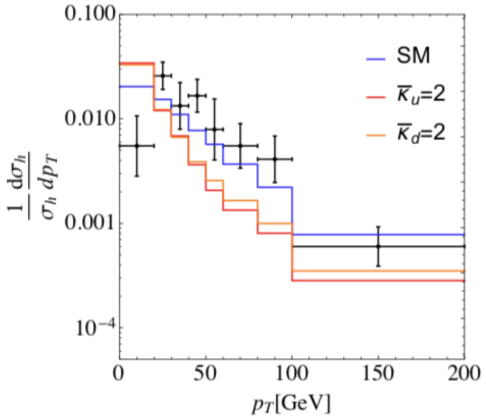
Y. Soreq, H.X. Zhu, J. Zupan, JHEP 12(2016)045
F. Bishara, U. Haisch, P. F. Monni, E. Re, PRL 118(2017)12,121801
G. Bonner, H. E. Logan, 1608.04376

$y_{u,d}/y_b < 0.4 \sim 0.5$

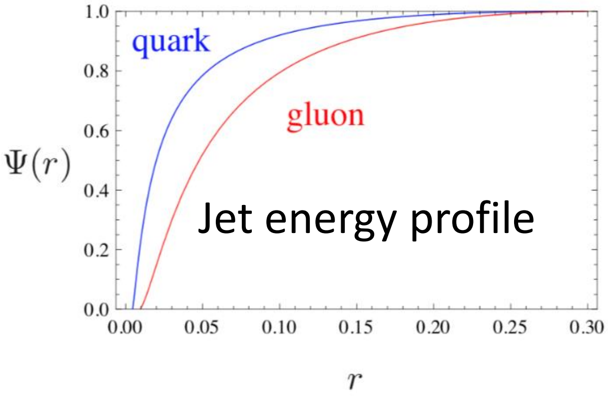
Soft gluon radiation

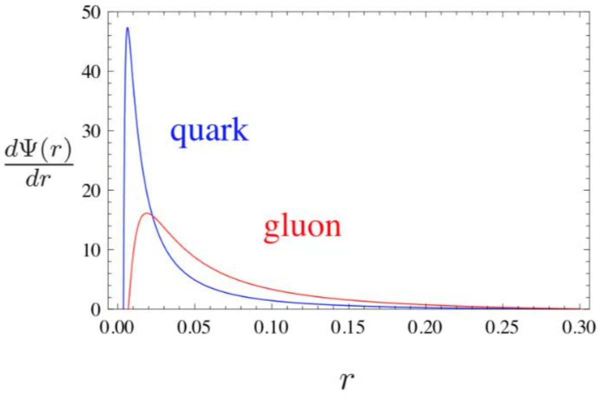




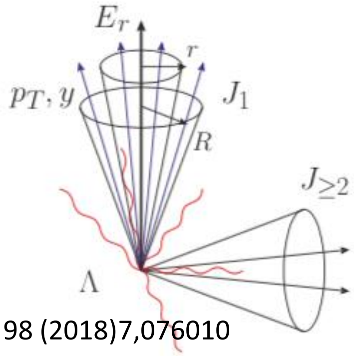


Light quark Yukawa couplings@ e^+e^-

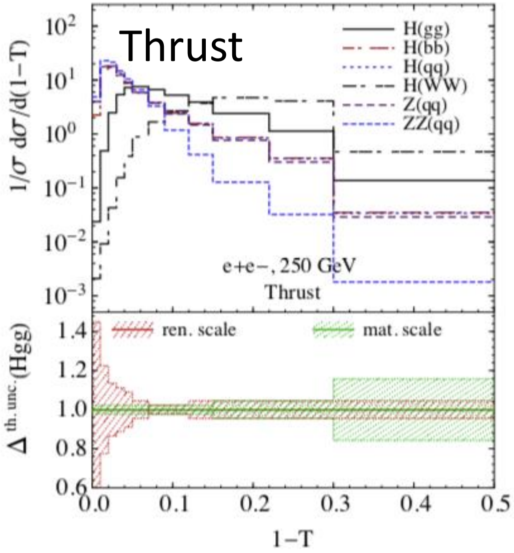


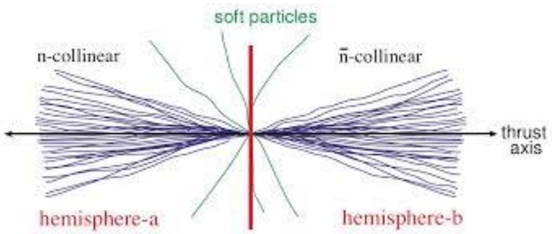


$$\Psi_J(r) = \frac{\sum_{i,d_{i,\hat{n}}<r} E_T^i}{\sum_{i,d_{i,\hat{n}}<R} E_T^i}$$



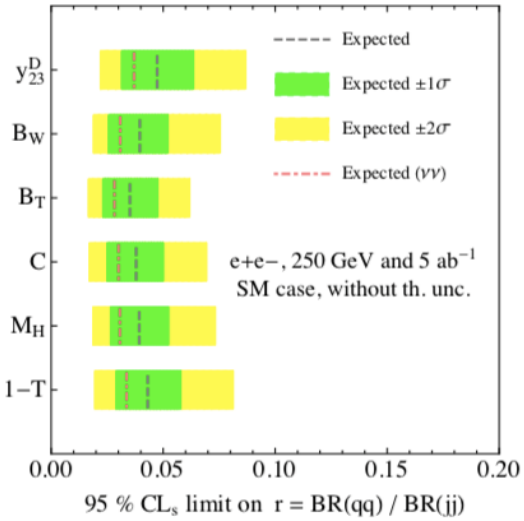
H. N. Li, Z. Li and C.-P. Yuan, PRL 107 (2011)152001; Y. T. Chien, I. Vitev, JHEP 12(2014)061
J. Isaacson, H.N. Li, Z. Li and C.-P. Yuan, PLB 771 (2017)619-623; G. X. Li, Z. Li, Y.D. Liu, Y. Wang, X. R. Zhao, PRD 98 (2018)7,076010





$$T = \max_{\vec{n}} \left(\frac{\sum_i |p_i \cdot \vec{n}|}{\sum_i |p_i|} \right)$$

$$y_{u,d,s}/y_b < 0.091$$



J. Gao, JHEP 01 (2018) 038

Event shapes

One class of event shapes:

$$e(X) = \frac{1}{Q}\sum_{i\in X}|p_\perp^i|\,f_e(\eta_i)$$

Examples:

Thrust $f_{1-T}(\eta) = e^{-|\eta|}$ Brandt, Peyrou, Sosnowski, Wroblewski,64; Farhi, 77

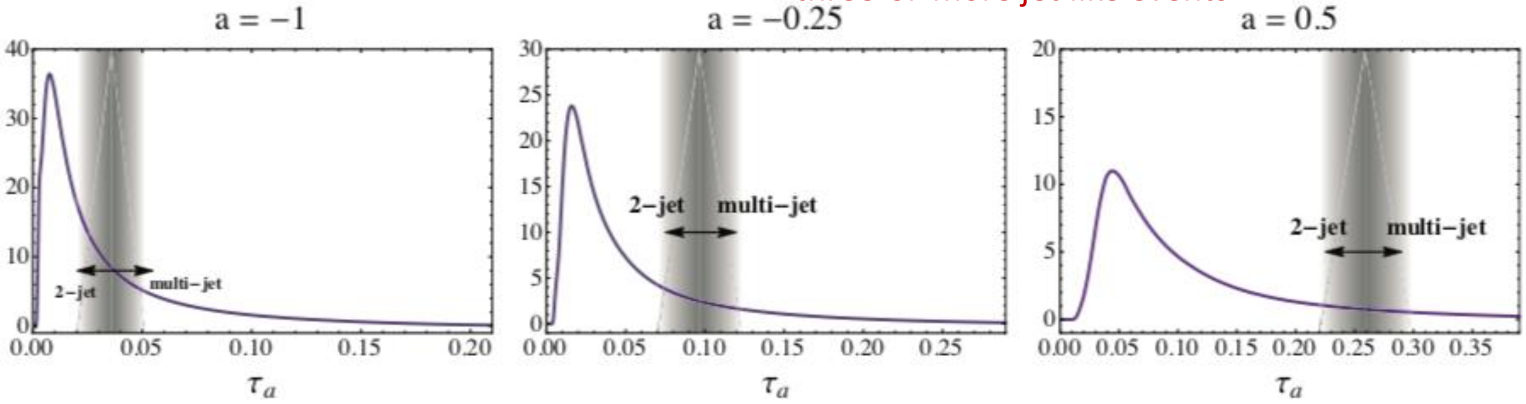
Jet broadening $f_B(\eta) = 1$ Catani, Turnock, Webber, 92

C-Parameter $f_C(\eta) = \dfrac{3}{\cosh(\eta)}$ Ellis, Ross, Terrano, 81

Angularities $f_{\tau_a}(\eta) = e^{-|\eta|(1-a)}$ Berger, Kucs, Sterman, 03 (relatively new)

The proportions of two jet-like and three-or-more jet like events

G. Bell, A. Hornig, C. Lee, J. Talbert, JHEP01(2019)147

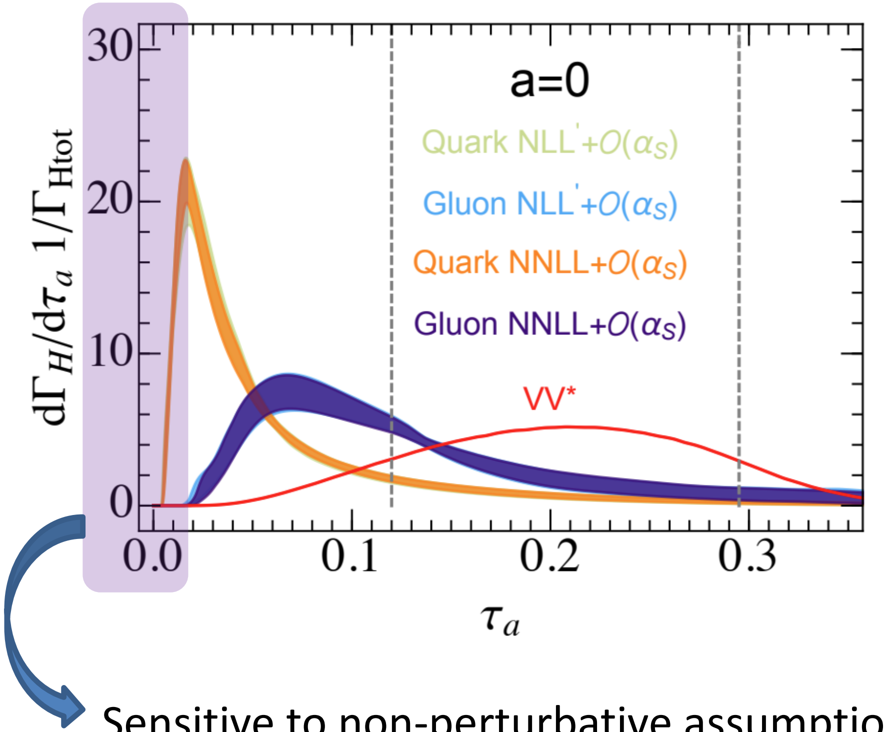


Higgs Yukawa couplings

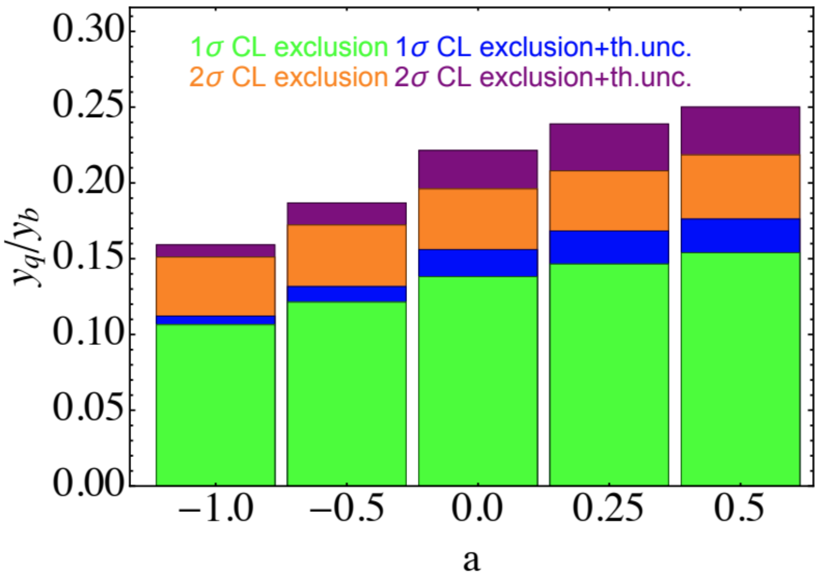
Bin Yan, C. Lee, JHEP 03 (2024) 123

Angularity distributions are very different for quark and gluon final state

Analysis Region

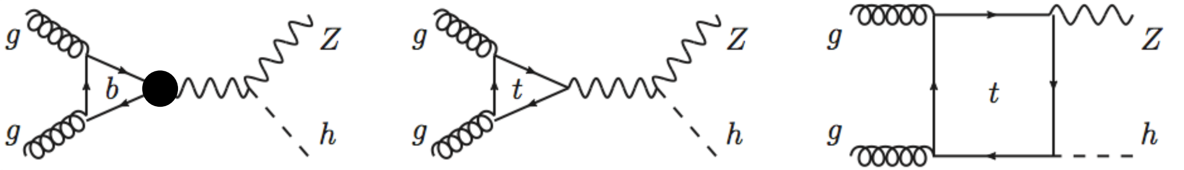


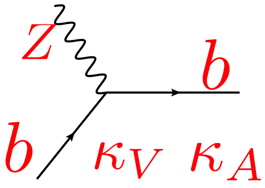
Sensitive to non-perturbative assumptions



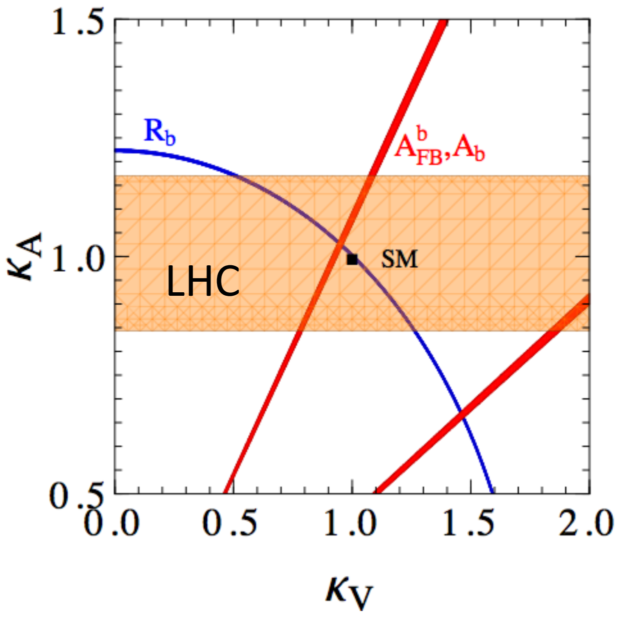
Electroweak properties for the SM

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



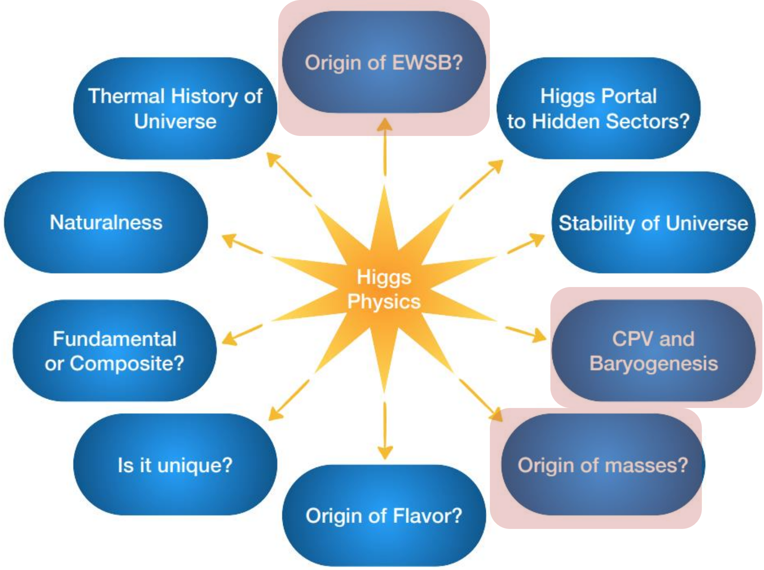
$$\mathcal{L} = \bar{b}\gamma_\mu(\kappa_V g_V - \kappa_A g_A \gamma_5) b Z_\mu$$

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



Thank you!