How to break EW symmetry naturally?

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ITP-CAS

C. Csaki, T. Ma, J. Shu., Phys.Rev.Lett. 119 (2017) no13, 131803
C. Csaki, T. Ma, J. Shu., Phys.Rev.Lett. 121 (2018) no23, 231801

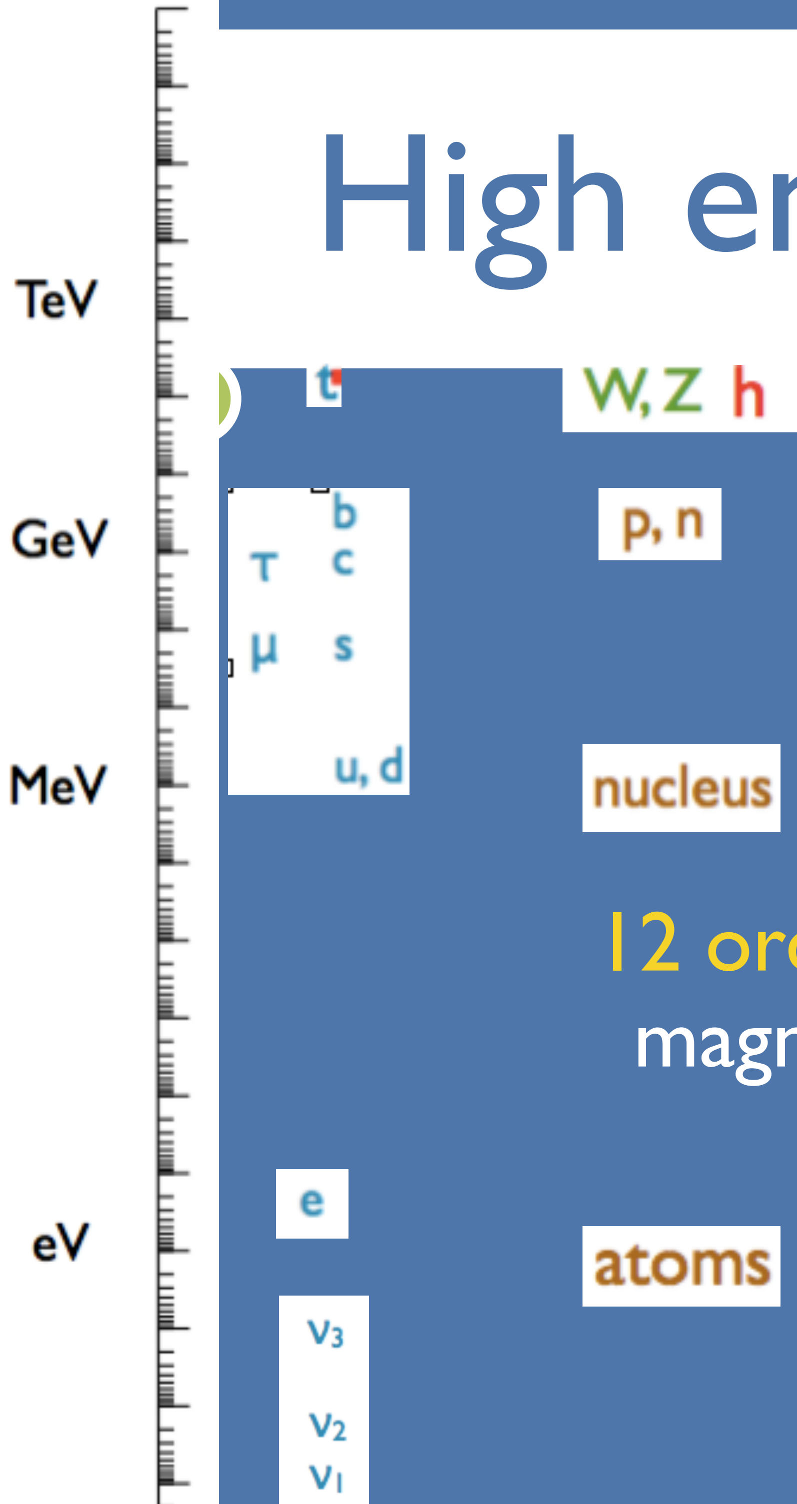
Many many other papers…………

C. Csaki, T. Ma, J. Shu, J-H. Yu, arxiv:1810.07704
C. Csaki, F. Freitas, L. Huang, T. Ma, J. Shu, M. Perelstein, arxiv:1811.01961

Outline

- Basic introduction
- Brief background knowledge on Maximally Symmetric Composite Higgs
- How to realize maximal symmetry, even from warped extra dimensions (emergence!!!)
- Naturalness sum rule, how to test?
- Trigonometric Parity for the Composite Higgs
- Outlook on HEP and other fields

High energy physics



2012

Higher and higher energy

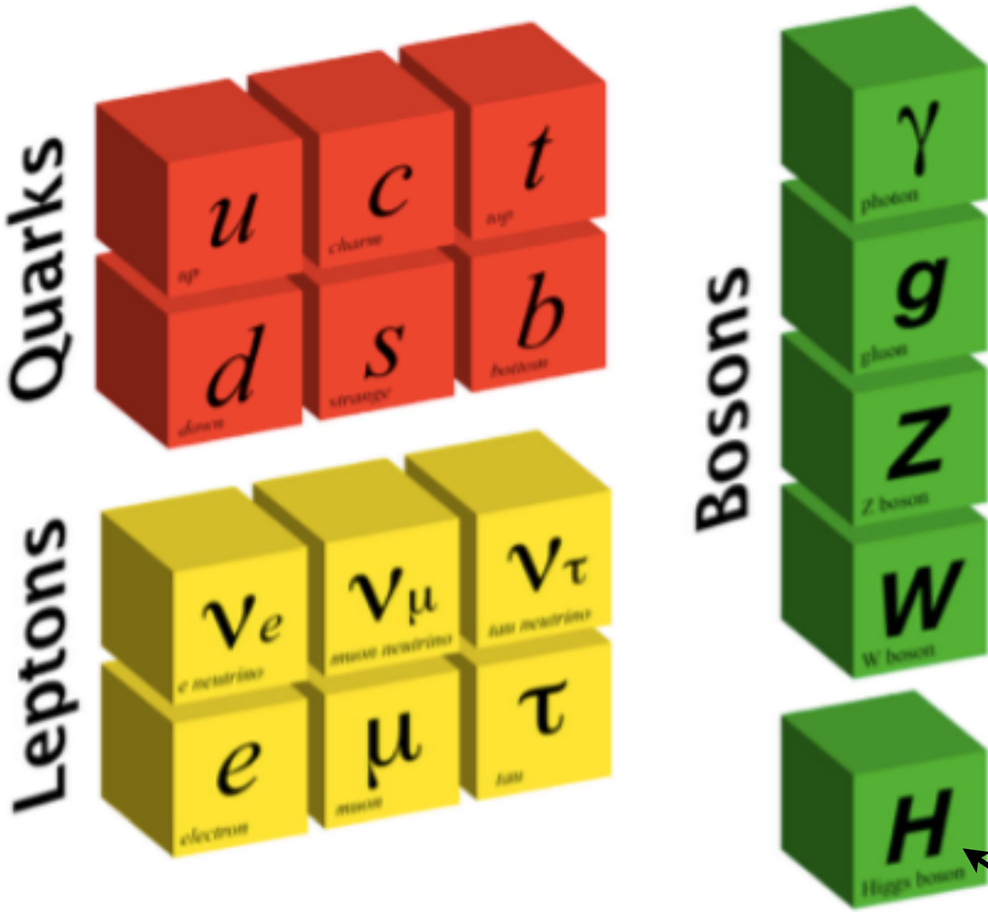
12 orders of magnitude

Last 122 years

1895

Open the door of sub-atom physics

"Old" physics up to date



The Weinberg-Salam Model

$$\mathcal{L} = \bar{E}_L(i\partial\!\!\!/)E_L + \bar{e}_R(i\partial\!\!\!/)e_R + \bar{Q}_L(i\partial\!\!\!/)Q_L + \bar{u}_R(i\partial\!\!\!/)u_R + \bar{d}_R($$

$$+ g(W_\mu^+ J_W^{\mu+} + W_\mu^- J_W^{\mu-} + Z_\mu^0 J_Z^\mu) + eA_\mu J_{EM}^\mu,$$

$$J_W^{\mu+} = \frac{1}{\sqrt{2}}(\bar{\nu}_L\gamma^\mu e_L + \bar{u}_L\gamma^\mu d_L);$$

$$J_W^{\mu-} = \frac{1}{\sqrt{2}}(\bar{e}_L\gamma^\mu \nu_L + \bar{d}_L\gamma^\mu u_L); \qquad e = \frac{gg'}{\sqrt{g^2+g'^2}}$$

$$J_Z^\mu = \frac{1}{\cos\theta_w}\Big[\bar{\nu}_L\gamma^\mu(\tfrac{1}{2})\nu_L + \bar{e}_L\gamma^\mu(-\tfrac{1}{2}+\sin^2\theta_w)e_L + \bar{e}_R\gamma^\mu($$

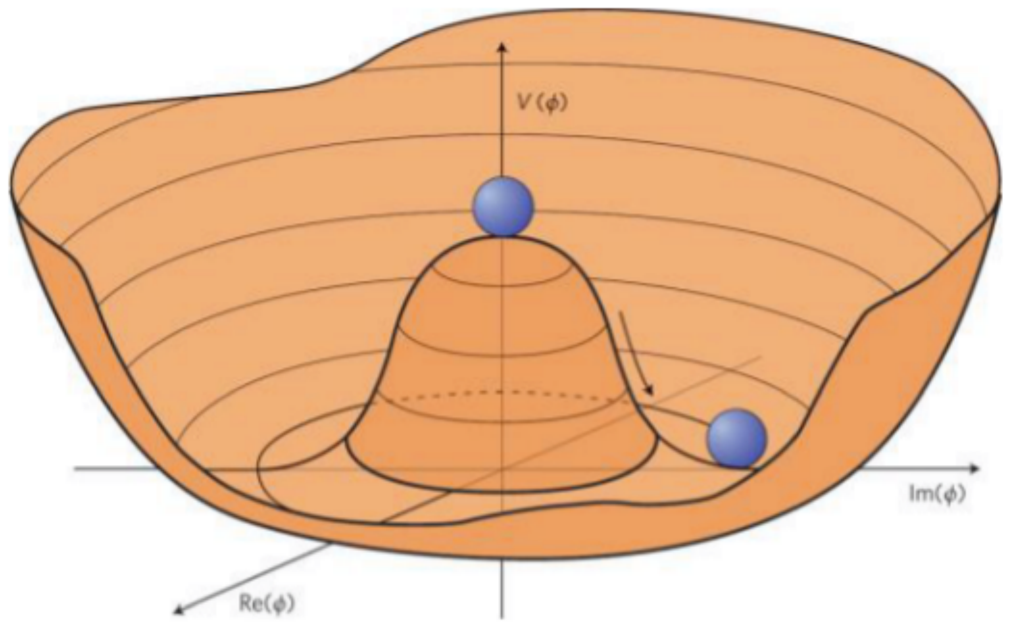
$$+ \bar{u}_L\gamma^\mu(\tfrac{1}{2} - \tfrac{2}{3}\sin^2\theta_w)u_L + +\bar{u}_R\gamma^\mu(-\tfrac{2}{3}\sin^2\theta_w)$$

$$+ \bar{d}_L\gamma^\mu(-\tfrac{1}{2} + \tfrac{1}{3}\sin^2\theta_w)d_L + \bar{d}_R\gamma^\mu(\tfrac{1}{3}\sin^2\theta_w)d$$

$$J_{EM}^\mu = \bar{e}\gamma^\mu(-1)e + \bar{u}\gamma^\mu(+\tfrac{2}{3})u + \bar{d}\gamma^\mu(-\tfrac{1}{3})d.$$

The chosen one!

Why God's particle?



Higgs potential

$$V(h) = \frac{1}{2}\mu^2 h^2 + \frac{\lambda}{4} h^4$$

EWSB
(Higgs mechanism)

$$\langle h \rangle \equiv v \neq 0 \;\; \rightarrow \;\; m_W = g_W \frac{v}{2}$$

Gives all particles mass

The origin of the mass

Unknown in "old" physics

Higgs potential

$$V(h) = \frac{1}{2}\mu^2 h^2 + \frac{\lambda}{4} h^4$$

Laudau-Ginzberg potential （Superconductivity）

negative， why?

$$m_h^2(h^\dagger h) + \frac{1}{2}\lambda(h^\dagger h)^2 + \frac{1}{3!\Lambda^2}(h^\dagger h)^3$$

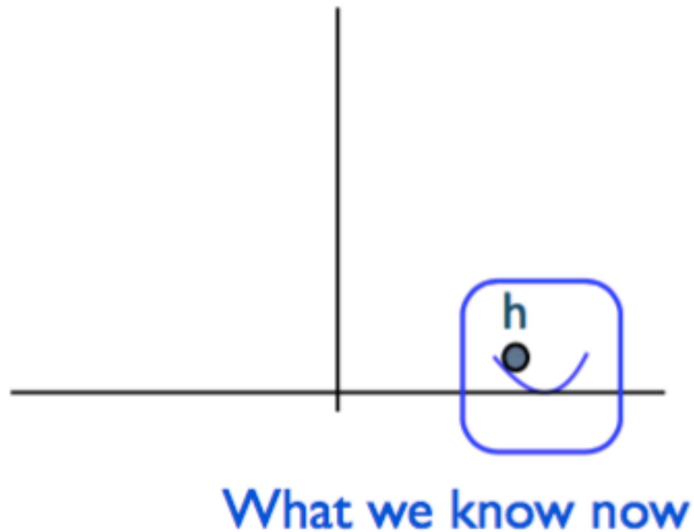
$$\frac{1}{2}\lambda(h^\dagger h)^2 \log\left[\frac{(h^\dagger h)}{m^2}\right]$$

$$V(h) \simeq -\gamma\, s_h^2 + \beta\, s_h^4\,.$$

We actually never know the Higgs potential and why EWSB?

CORE question in particle physics

Unknown in “old” physics



Tayler expand on the quantum fluctuation of higgs potential

h^3 h^4 h^5。。。。。h^9

Future Collider

Not known how to probe

$$V(h) = \frac{1}{2}\mu^2 h^2 + \frac{\lambda}{4} h^4$$

$$V(h) = \frac{1}{2}\mu^2 h^2 - \frac{\lambda}{4} h^4 + \frac{1}{\Lambda^2} h^6$$

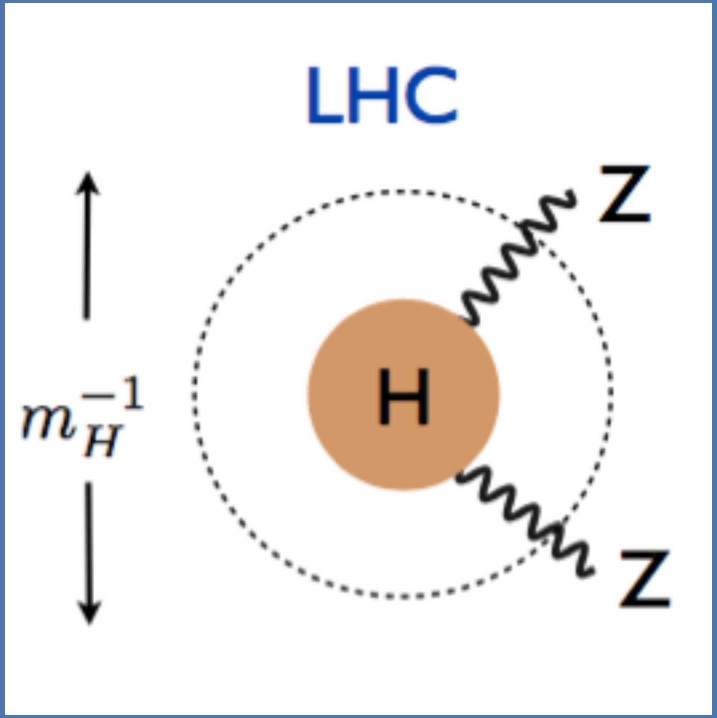
Same collider signal, different potential

Substructure of Higgs?

Suppose in NP scale, we see substructure of Higgs （like QCD Pi form factor deviations）

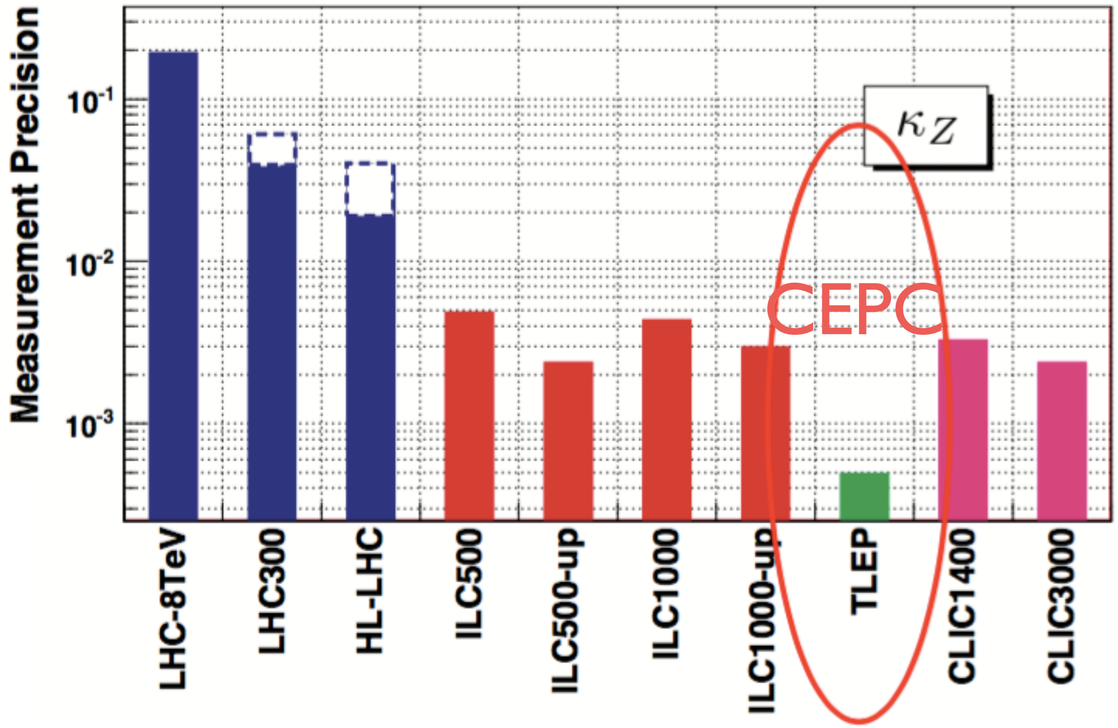
Possible NP deviation

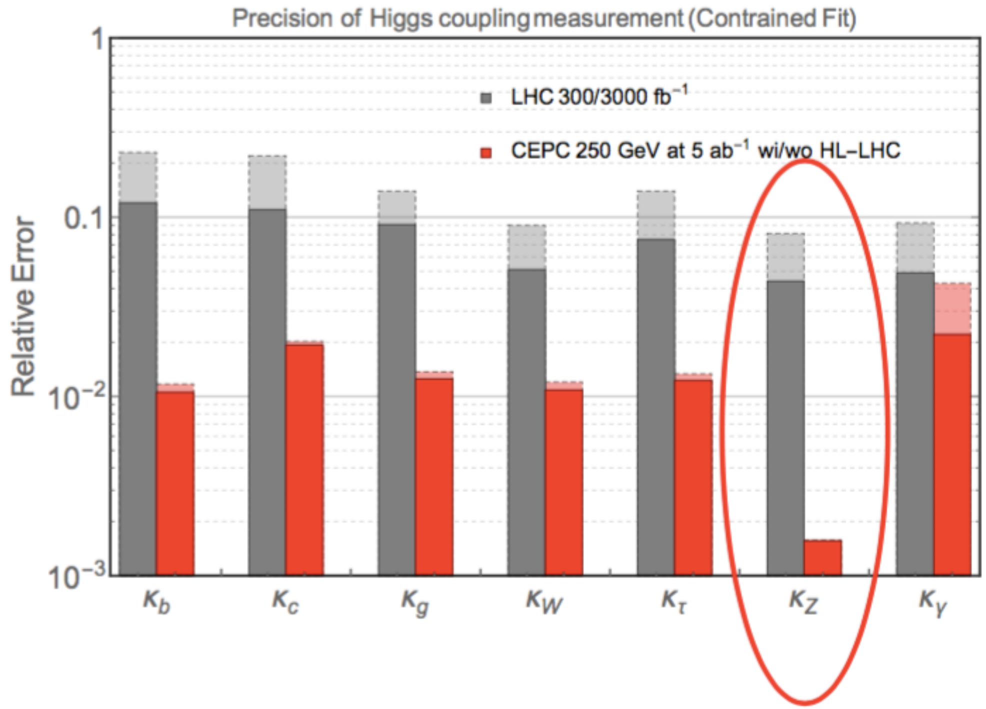
$$\delta = c\frac{m_W^2}{M_{\rm NP}^2},\ c = \mathcal{O}(1)$$

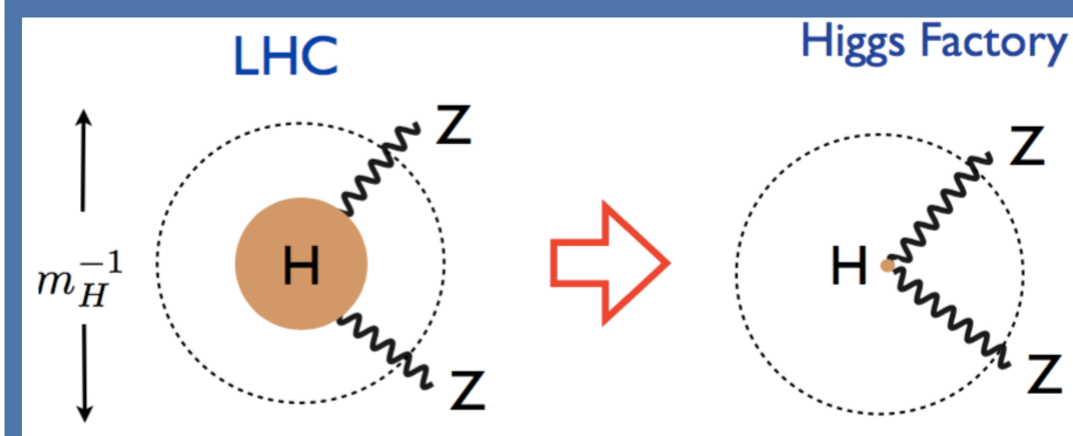


Precision Higgs measure

$$\kappa_Z = \frac{g_{hZ}(\text{Measured})}{g_{hZ}(\text{SM})}$$







Higgs compositeness for Higgs factory

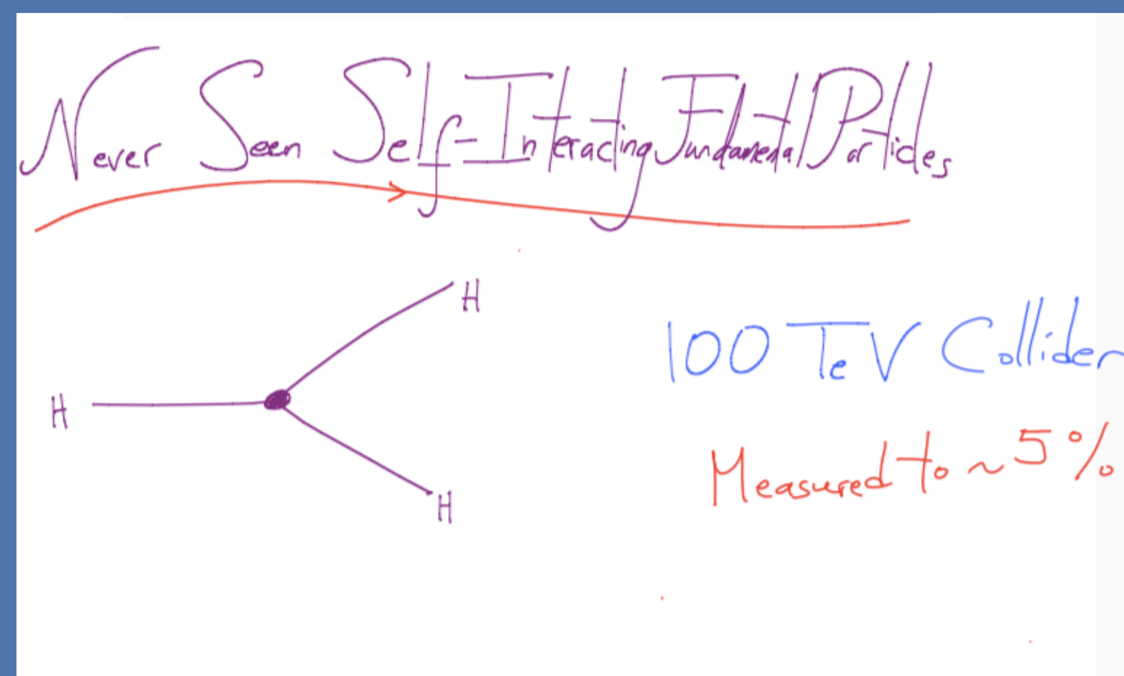
Our chairman Mao says all particles are composite from his philosophy!

A great eye-catching and physics motivation for Higgs factory and great collider

Nima's talk in IHEP 2018

Higgs precision

Self-interaction



Higgs as a pNGB

Why Higgs as a pNGB?

Kaplan, H. Georgi, Phys.Lett.B 136 (1984) 183
Kaplan, H. Georgi, Phys.Lett.B 145 (1984) 216

- Higgs mass small comping to confinement scale (1~10TeV)

Highly constrained by LEP

- The radiatively generated Higgs potential
- universal prediction on Higgs couplings (Like pion soft theorem)

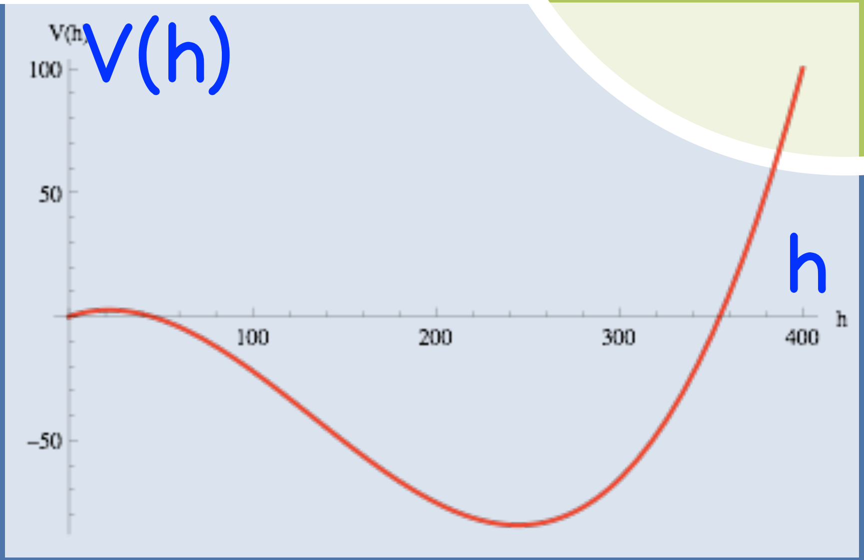
If the strong dynamics triggers the breaking G/H, pNGB is a composite particle.

QCD chiral symmetry, pion

The origin of Higgs potential

But pions has no vev

only a positive mass



The origin of the Higgs potential

- The "parton" mass for the composite Higgs

L. Da, T. Ma, J. Shu, in preparation

- Quantum corrections from the SM particles (Mostly top)?

More focused top sector

Maximally symmetric composite Higgs

Why another CHM?

- Can get the correct EWSB.
- Can easily get the 125 GeV light Higgs mass?
- No UV dependence of Higgs potential.

gauge hierarchy problem

- Can we have minimal technical tuning

- A general methods based on symmetric coset space to describe the EWSB (Higgs as a pNGB) in an unified manner.

Simplest Structure

- Find the new symmetry breaking pattern (Maximal symmetry) automatically solves all problems above

C. Csaki, T. Ma, J. Shu., Phys.Rev.Lett. 119 (2017) no13, 131803

Symmetric space

For any global symmetry G breaks into H

$T^{\hat{a}}(T^{a})$ is the (un)broken generator

$[T^a, T^a] \sim T^a, \; [T^a, T^{\hat{a}}] \sim T^{\hat{a}}$

H is a closed group

$[T^{\hat{a}}, T^{\hat{a}}] \sim T^a$

symmetric coset space

G always has an automorphism

$VT^aV^\dagger = T^a$

$VT^{\hat{a}}V^\dagger = -T^{\hat{a}}$

Higgs is the NGB in the symmetric coset space

V is also the Higgs parity operator, like pion parity in QCD

Examples:

Examples of Symmetric Coset Space:

$$SU(M+N)/SU(M)\times SU(N)\times U(1)$$

$$SO(M+N)/SO(M)\times SO(N)$$

$$V=\begin{pmatrix}1&&&&\\&1&&&\\&&\ddots&&\\&&&-1&\\&&&&-1\end{pmatrix}$$

$$SO(5)/SO(4)$$

$$V=\begin{pmatrix}\mathbf{1}_{4\times4}&0\\0&-1\end{pmatrix}$$

$$SU(2N)/Sp(2N)$$

$$\Phi=\mathbf{1}_{N\times N}\times(i\sigma_2)$$

$$SU(N)/SO(N)$$

$$\Phi=\begin{pmatrix}0&1_{\frac{N}{2}\times\frac{N}{2}}\\1_{\frac{N}{2}\times\frac{N}{2}}&0\end{pmatrix}\quad N=2l$$

$$\Phi=\begin{pmatrix}0&&1_{\frac{N-1}{2}\times\frac{N-1}{2}}\\0&1&0\\1_{\frac{N-1}{2}\times\frac{N-1}{2}}&&0\end{pmatrix}\quad N=2l+1$$

$$G\times G/G_V$$

Actually cover almost all useful cosets

Goldstone in symmetric space

For any global symmetry G spontaneously breaks into H

If decouple the "Higgs"

$$U = \exp\left(\frac{ih^{\hat{a}}T^{\hat{a}}}{f}\right)$$

The CCWZ transformation

$$U \to gUh(h^{\hat{a}}, g)^{\dagger}$$

For any symmetric coset space

Key construction

$$\Sigma' = U^2 V$$

Information of G/H is included in V

$$\tilde{U} = VUV^{\dagger} = U^{\dagger}.$$

Simple linear transformation

$$\Sigma' \to g\Sigma' g^{\dagger} \ .$$

Goldstone matrix transform linearly!

G/H CW potential from top

Consider the MCHM5 SO(5)/SO(4)

SM Fermion

Embed the SM fields into fund rep of G (spurionic)

$$\Psi_{q_L} = \frac{1}{\sqrt{2}} \begin{pmatrix} b_L \\ -ib_L \\ t_L \\ it_L \\ 0 \end{pmatrix} \qquad \Psi_{t_R} = \begin{pmatrix} 0 \\ 0 \\ 0 \\ 0 \\ t_R \end{pmatrix}$$

$$\Sigma' \to g\Sigma' g^\dagger \; .$$

$$\Lambda^L = \frac{1}{\sqrt{2}} \begin{pmatrix} 0 & 0 & 1 & -i & 0 \\ 1 & i & 0 & 0 & 0 \end{pmatrix}$$

spurion vev

$$\Lambda^R = \begin{pmatrix} 0 & 0 & 0 & 0 & 1 \end{pmatrix}$$

$$\Sigma' = \begin{pmatrix} 1 & 0 & 0 & 0 & 0 \\ 0 & 1 & 0 & 0 & 0 \\ 0 & 0 & 1 & 0 & 0 \\ 0 & 0 & 0 & c_{2h} & -s_{2h} \\ 0 & 0 & 0 & -s_{2h} & -c_{2h} \end{pmatrix}$$

$$\Psi_{Q_L} = \Lambda_L^\alpha Q_L^\alpha$$

$$\Psi_{t_R} = \Lambda_R t_R$$

Q_L^α t_R SU(2) multiplet

G/H CW potential from top

Most general Lagrangian $\Sigma'^2 = 1$

$$\Sigma' \to g\Sigma' g^\dagger \ .$$

Master formular

$$\mathcal{L}_{\rm eff} = \bar\Psi_{Q_L} \not p (\Pi_0^q(p) + \Pi_1^q(p)\Sigma')\Psi_{Q_L} + \bar\Psi_{t_R} \not p (\Pi_0^t(p) + \Pi_1^t(p)\Sigma')\Psi_{t_R} + \bar\Psi_{Q_L} M_1^t(p)\Sigma'\Psi_{t_R} + h.c.$$

$\Psi \to g\Psi$ fund rep

Derivatives of GB does not contribute to Higgs potential

Converting back to the SM fields by using spurions.

$$\mathcal{L}_{\rm eff} = \bar Q_L^\alpha \not p {\rm Tr}[(\Pi_0^q + \Pi_1^q\Sigma')P_l^{\alpha\beta}]Q_L^\beta + \bar t_R \not p {\rm Tr}[(\Pi_0^t + \Pi_1^t\Sigma')P_r]t_R + M_1^t \bar Q_L^\alpha t_R {\rm Tr}[\Sigma'.P_{lr}^\alpha] \ ,$$

$$P_l^{\alpha\beta} = (\Lambda_L^\beta)^\dagger \Lambda_L^\alpha, \ P_r = (\Lambda_R)^\dagger \Lambda_R \quad P_{lr}^\alpha = (\Lambda_R)^\dagger \Lambda_L^\alpha.$$

Master formular

Based on G/H, one can write whatever Lag contribute to Higgs potential

Enlarged Global Symmetry

$\Pi_1^{q,t} = 0$ LH & RH top each has $G_L \times G_R$ symmetry

global

Only acting on fermions, not Goldstones

G_L $\Psi_{Q_L} \to g_L \Psi_{Q_L}$

G_L $\Psi_{t_R} \to g_R \Psi_{t_R}$

Only the mass term breaks them into $G_{V'}$

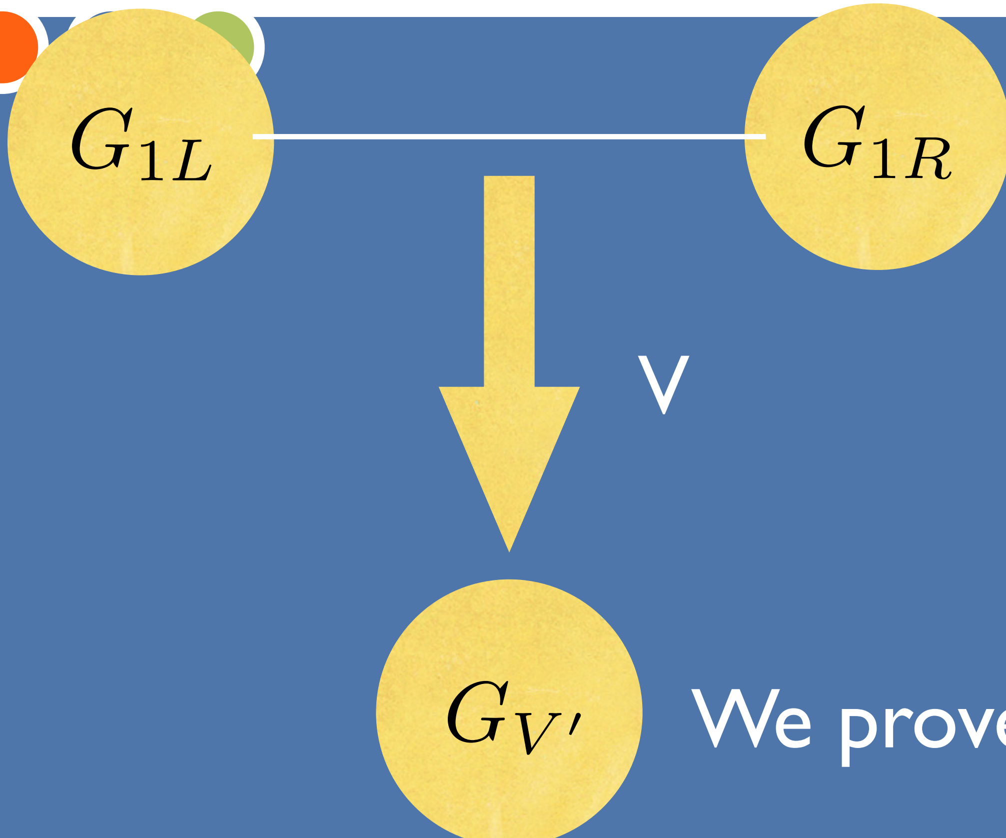
$g_L \Sigma' g_R^\dagger = \Sigma'$. Maximal subgroup leaves the GB invariant

$g'_{L,R} = U^\dagger g_{L,R} U$

$g'_L V {g'_R}^\dagger = V$

Global Symmetry from composites

What is Maximal Symmetry?



We prove

SO(5)/SO(4)

$$V = \begin{pmatrix} \mathbf{1}_{4\times 4} & 0 \\ 0 & -1 \end{pmatrix}$$

$$H_V$$

$$(G/H)_A$$

Mathematical structure

Can be used as a new UV completion of maximal symmetry just like moose model for LH,

C. Csaki, T. Ma, J. Shu., Phys.Rev.Lett. 119 (2017) no13, 131803

Appendix A

The Higgs potential

sin(2h/f)

$$V(h) = -2N_c \int \frac{d^4p}{2\pi^4} \log\left[1 + \frac{(M_1^t)^2 |\mathrm{Tr}[\Sigma'.P_{lr}^1]|^2}{p^2 \mathrm{Tr}[\Pi_0^q P_l^{11}]\mathrm{Tr}[\Pi_0^t P_r]}\right]$$

Higgs potential is just the top mass square up to some factors after integration on momentum.

Log(1+x) expansion

CW potential

top mass from both LH & RH top mixture with top partners

No UV Divergence

$$M_1^t \sim \lambda_L \lambda_R f^2 (M_Q - M_S)/p^2$$

$$V(h) \sim \lambda_L^2 \lambda_R^2 f^4 (M_Q - M_S)^2/\Lambda^2$$

$$m_t \sim \sin_{2h}$$

Higgs potential $(\sin_{2h})^2 = s_h^2 - s_h^4.$

Understand deconstruction

Collective Symmetry Breaking, "Little Higgs"

$\sim \int d^4p \Pi_1^{q,t}$

$\Pi_1^{q,t} \propto p^{-2N}$ at UV

G/H → G/H G/H G/H

One need 3 G/H structures

N=3 for finite potential

Even for large N, still have very troublesome finite piece

Higgs potential tends to have large v/f>1 (double tuning)

Higgs mass tends to be large than 300GeV

Fine-tuning

Realization from MCHM5

Fermion mass from linear mixing

$$\mathcal{L}_{mix} = \lambda \bar{q}_i \mathcal{O}_i$$

$$\mathcal{O}_i \sim U\Psi_i$$

partial compositeness

$$\mathcal{L} = \lambda_L \bar{q}^{\alpha}_L \Lambda^L_{\alpha I} \mathcal{O}^I_R + \lambda_R \bar{t}_R \Lambda^R_{\alpha I} \mathcal{O}^I_L + h.c$$

5=4+1 Composite top partners

$$\Psi_Q = \frac{1}{\sqrt{2}} \begin{pmatrix} iB - iX_{5/3} \\ B + X_{5/3} \\ iT + iX_{2/3} \\ -T + X_{2/3} \\ 0 \end{pmatrix} \qquad \Psi_S = \begin{pmatrix} 0 \\ 0 \\ 0 \\ 0 \\ T_1 \end{pmatrix}$$

$$U \to gUh(h^{\hat{a}}, g)^{\dagger}$$

Fermionic Lagrangian:

$$\begin{aligned} \mathcal{L}_f &= \bar{\Psi}_Q(i\not{D} - M_Q)\Psi_Q + \bar{\Psi}_S(i\not{D} - M_S)\Psi_S \\ &+ \frac{\lambda_R f}{\sqrt{2}} \bar{\Psi}_{t_R} P_L(\epsilon_{tS} U\Psi_S + \epsilon_{tQ} U\Psi_Q) \\ &+ \lambda_L f \bar{\Psi}_{q_L} P_R(\epsilon_{qS} U\Psi_S + \epsilon_{qQ} U\Psi_Q) + h.c, \end{aligned}$$

Top and top partner masses:

$$m_t = \frac{\epsilon_{qQ}\epsilon_{tS} f^2}{2M_T M_{T_1}} \left| \frac{\epsilon_{qS}}{\epsilon_{qQ}} M_Q - \frac{\epsilon_{tQ}}{\epsilon_{tS}} M_S \right| \sin\frac{\langle h \rangle}{f}$$

$$M_T = \sqrt{\epsilon^2_{qQ} f^2 + M^2_Q}, \quad M_{T_1} = \sqrt{\frac{\epsilon^2_{tS}}{2} f^2 + M^2_S}.$$

The use of V

Rewrite the top partners into a full rep of G

$$\Psi_+ = V\Psi_- \quad V = \begin{pmatrix} 1_{4\times 4} & 0 \\ 0 & -1 \end{pmatrix}$$

$$\Psi_+ = \frac{1}{\sqrt{2}}(\Psi_2 + \Psi_1) \quad \Psi_- = \frac{1}{\sqrt{2}}(\Psi_2 - \Psi_1)$$

$$c_{\pm R} = \frac{\epsilon_{tQ} \pm \epsilon_{tS}}{2}, \; c_{\pm L} = \frac{\epsilon_{qQ} \pm \epsilon_{qS}}{\sqrt{2}}.$$

The Lagrangian is G invariant except for V

Elementary-composite mixing is G invariant

$$c_{-L} = c_{-R} = 0.$$

$$\begin{aligned}\mathcal{L}_f =& \bar{\Psi}_+ i\not{\nabla}\Psi_+ + \bar{\Psi}_- i\not{\nabla}\Psi_- + \lambda_R f c_{+R} \bar{\Psi}_{t_R} P_L U \Psi_+ \\ &+ \lambda_L f c_{+L} \bar{\Psi}_{q_L} P_R U \Psi_+ - (M_Q + M_S)\bar{\Psi}_{+L}\Psi_{+R} \\ &- (M_Q - M_S)\bar{\Psi}_{+L} V \Psi_{+R} + h.c. \qquad (22)\end{aligned}$$

Enlarged global sym:

$$SO(5)_L \times SO(5)_R$$

Symmetries in CS

Two vector mass: twisted and untwisted:

$SO(5)_L$ $\quad \Psi_{+L} \;\rightarrow\; g'_L \Psi_{+L}$

$SO(5)_R$ $\quad \Psi_{+L} \;\rightarrow\; g'_L \Psi_{+L}$

The mass term explicitly break the global symmetry

Maximal Symmetry: Only the Twisted Mass

$$M_Q - M_S = 0 \Rightarrow SO(5)_L \times SO(5)_R / SO(5)_V$$
$$M_Q + M_S = 0 \Rightarrow SO(5)_L \times SO(5)_R / SO(5)_{V'} \qquad g'_L V {g'_R}^\dagger \;=\; V$$
$$|M_Q| \neq |M_S| \Rightarrow SO(5)_L \times SO(5)_R / SO(4)_V \quad (23)$$

The form factors

Integrating out the top partners, we have the form factors in the EFT

$$\frac{\Pi_0^{q,t}}{\lambda_{L,R}^2 f^2} = 1 + \frac{(c_{-L,R}^2 + c_{+L,R}^2)(M_Q^2 + M_S^2 - 2p^2)}{2(p^2 - M_S^2)(M_Q^2 - p^2)} + \frac{c_{-L,R}c_{+L,R}(M_S + M_Q)(M_S - M_Q)}{(p^2 - M_S^2)(M_Q^2 - p^2)}$$

$$\frac{\Pi_1^{q,t}}{\lambda_{L,R}^2 f^2} = \frac{c_{+L,R}c_{-L,R}(M_Q^2 + M_S^2 - 2p^2)}{(p^2 - M_S^2)(M_Q^2 - p^2)} + \frac{(c_{+L,R}^2 + c_{-L,R}^2)(M_S - M_Q)(M_S + M_Q)}{2(p^2 - M_S^2)(M_Q^2 - p^2)}$$

$$\frac{M_1^t}{\lambda_L \lambda_R f^2} = \frac{M_Q^2 M_S(c_{-L} - c_{+L})(c_{-R} - c_{+R})}{2(p^2 - M_Q^2)(p^2 - M_S^2)} - \frac{M_S^2 M_Q(c_{-L} + c_{+L})(c_{-R} + c_{+R})}{2(p^2 - M_Q^2)(p^2 - M_S^2)} + \frac{M_Q(c_{-L} + c_{+L})(c_{-R} + c_{+R})p^2}{2(p^2 - M_Q^2)(p^2 - M_S^2)} - \frac{M_S(c_{-L} - c_{+L})(c_{-R} - c_{+R})p^2}{2(p^2 - M_Q^2)(p^2 - M_S^2)}, \quad (54)$$

Vh structure from symmetry

$SO(5)_{V'}$

UV finite

c_{+L} is turned off, Higgs shift symmetry $h^{\hat{a}} \to h^{\hat{a}} + \alpha^{\hat{a}}$

$$\Psi_{+L} \to g'_L \Psi_{+L}$$

$$\Psi_{+R} \to V g'_L \Psi_{+R}$$

subgroup of transformation on the left

$$(g'_L = \exp(i\alpha^{\hat{a}} T^{\hat{a}}))$$

$$|\lambda_L \lambda_R|^2 c_{+L}^2 c_{+R}^2 f^4 (M_1 - M_2)^2 / \Lambda^2. \qquad (26)$$

Top mass square!

$$m_t = c_{+L} c_{+R} (M_Q - M_S) f^2 / (2 M_T M_{T_1})$$

$SO(4)_V$

Log divergent

$$V_{L\xi} \sim |\lambda_L|^2 c_{+L}^2 f^2 (M_1 + M_2)(M_1 - M_2) \log \Lambda^2 \quad (24)$$

Higgs potential tuning

$$V_f(h) \simeq -\gamma_f s_h^2 + \beta_f s_h^4,$$

$$\xi = \frac{\gamma_f}{2\beta_f}$$

To obtain $\xi \ll 1$

$\gamma_{\rm div}$ much smaller than $\beta_{\rm div}$

$$V_{\rm div} = \frac{N_c M_f^4}{16\pi^2 g_f^2}[(\frac{c_L}{2}\epsilon_L^2 - c_R\epsilon_R^2 + c_{LL}\frac{\epsilon_L^4}{g_f^2} + c_{RR}\frac{\epsilon_R^4}{g_f^2})s_h^2 + (c'_{LL}\frac{\epsilon_L^4}{g_f^2} + c'_{RR}\frac{\epsilon_R^4}{g_f^2})s_h^4] \equiv -\gamma_{\rm div}s_h^2 + \beta_{\rm div}s_h^4 \quad (34)$$

Large finite piece from \PI_1 form factor (expansion over s_h or c_h) tends to make \gamma >> \beta

quadratic divergent parts $\mathcal{O}(\epsilon_L^2)$ and $\mathcal{O}(\epsilon_R^2)$

$$c_L \sim c_R \sim \Lambda^2$$

log divergent $\mathcal{O}(\epsilon_L^4)$ and $\mathcal{O}(\epsilon_R^4)$.

$$c_{LL} \sim c'_{LL} \sim c_{RR} \sim c'_{RR} \sim \log\Lambda$$

If UV divs cancels but finite remains $\Delta^{5+5} \simeq \frac{1}{\xi}\frac{g_f^2}{\epsilon^2}$ Double tuning

G. Panico, M. Redi, A. Tesi, A. Wulzer, JHEP 1303, 053 (2013)

Tunnings in EWSB

$$V_h = c_{LR}\frac{N_c M_f^4}{16\pi^2}\left(\frac{\epsilon_L^2\epsilon_R^2}{g_f^4}\right)[-s_h^2+s_h^4]+\mathcal{O}(\frac{\epsilon_L^4\epsilon_R^4}{g_f^8})$$
$$\simeq c_{LR}\frac{N_c M_f^4}{16\pi^2}\left(\frac{y_t}{g_f}\right)^2[-s_h^2+s_h^4]+\mathcal{O}(\frac{y_t^4}{g_f^4})$$
$$\equiv -\gamma_f s_h^2+\beta_f s_h^4 \quad (39)$$

Maximally symmetric case

$$\xi = \frac{\gamma_f}{2\beta_f} = 0.5$$

Cancellation from the gauge sector

$$\gamma_g = -\frac{9 f^2 g^2 m_\rho^2 \log 2}{64\pi^2}$$

$\xi \ll 1$, we require $\gamma_f \simeq -\gamma_g$.

Assuming 1st & 2nd Weinberg sum rule, UV finite

$$\Delta^{(5+5)} = \frac{\max(|\gamma_f|,|\gamma_g|)}{|\gamma_f+\gamma_g|} \simeq \max(\frac{1}{2\xi},\frac{1}{2\xi}-1) = \frac{1}{2\xi} \quad (44)$$

20% tuning

How to get 125 GeV Higgs?

$$m_t \sim \sin\theta_L \sin\theta_R\,|M_Q - M_S| s_h$$

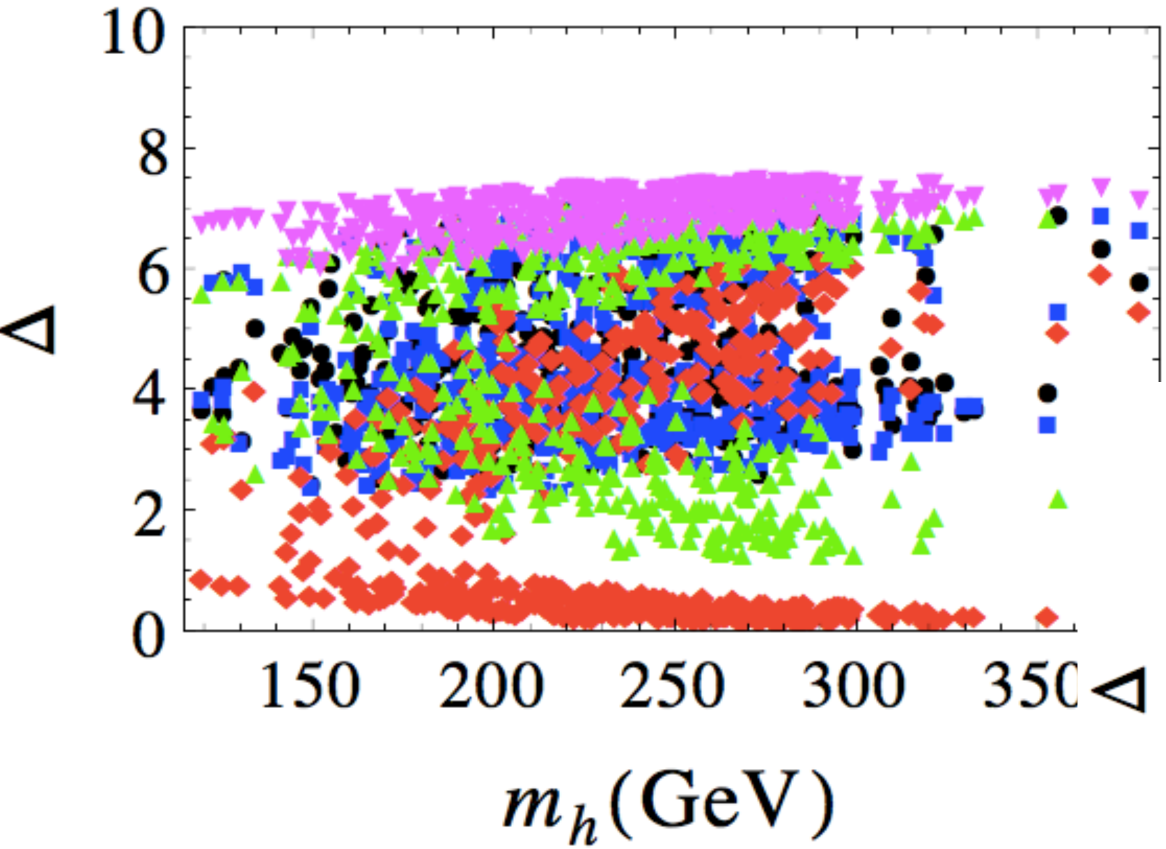
Usually top is too heavy, difficult to get a light Higgs

θ_L and θ_R minimal $M_Q = -M_S$

$\min\{M_T, M_{T_1}\} = \min\{\frac{M_S}{\cos\theta_L}, \frac{M_Q}{\cos\theta_R}\}$ minimal

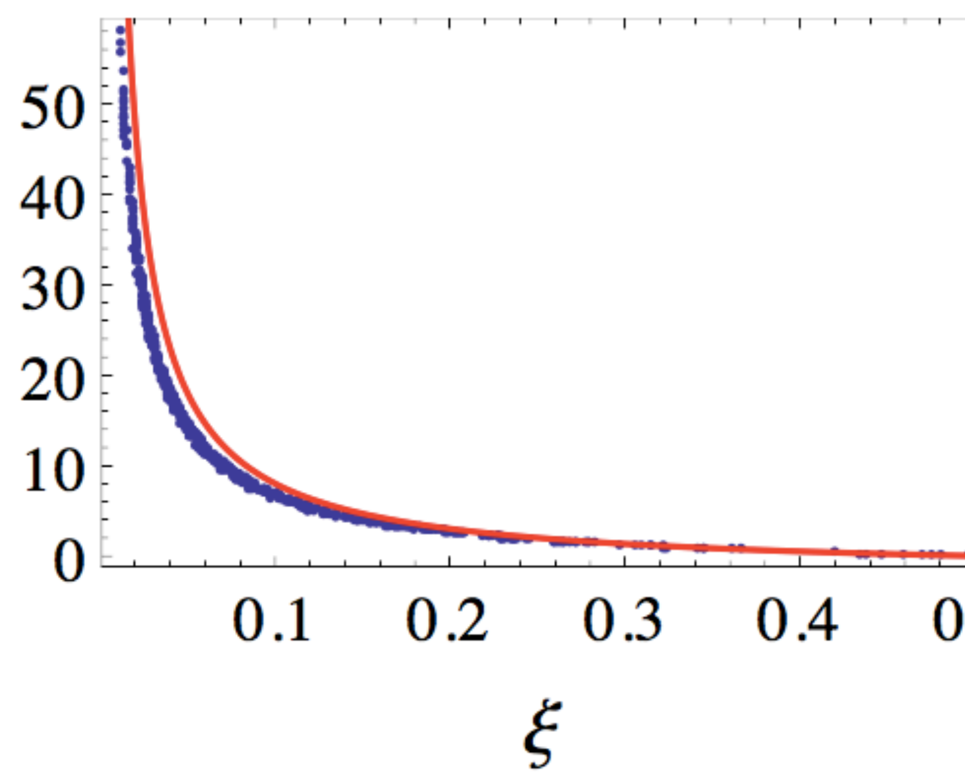
$$m_H \propto \min\{M_T, M_{T_1}\} m_t / f$$

Numerical tuning



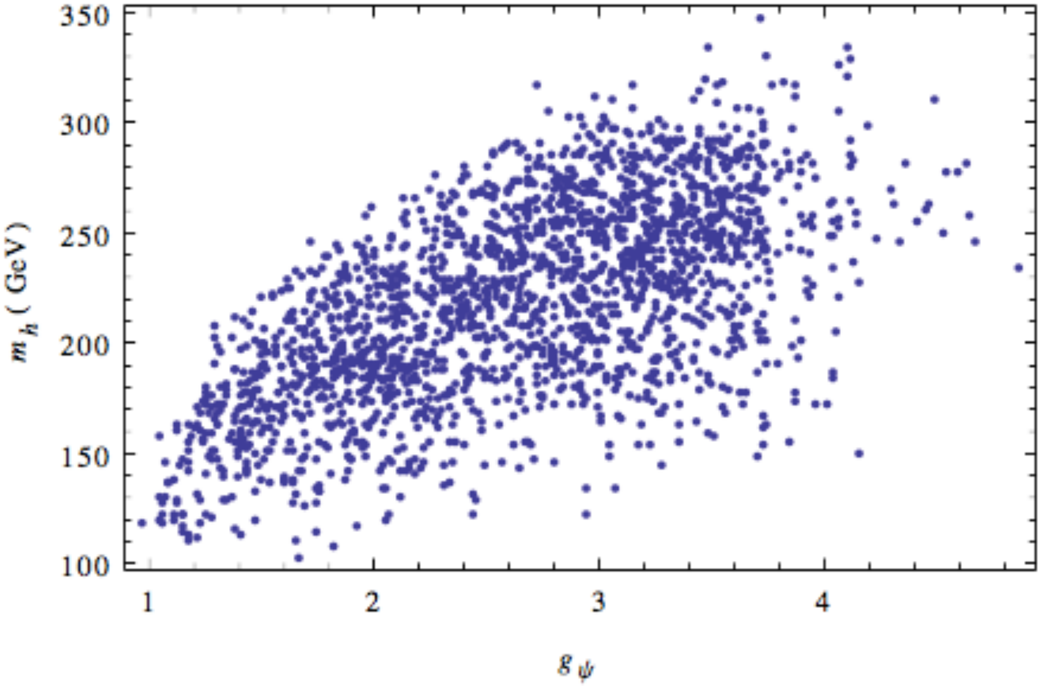
$$\Delta_m \simeq 2\gamma_g/|\gamma_f+\gamma_g| \simeq \frac{1}{\xi}-2$$

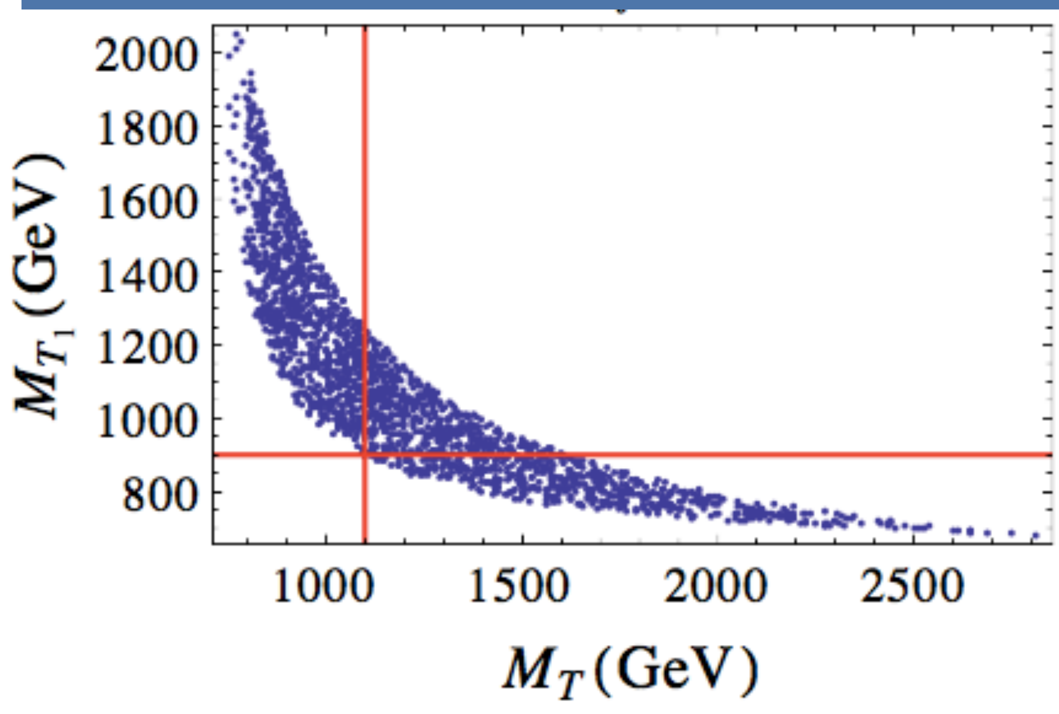
One free parameter except f



$$\Delta = \max\left|\frac{2x_i}{s_h}\,\frac{c_h^2}{f^2 m_h^2}\,\frac{\partial^2 V}{\partial x_i \partial s_h}\right|$$

Scan



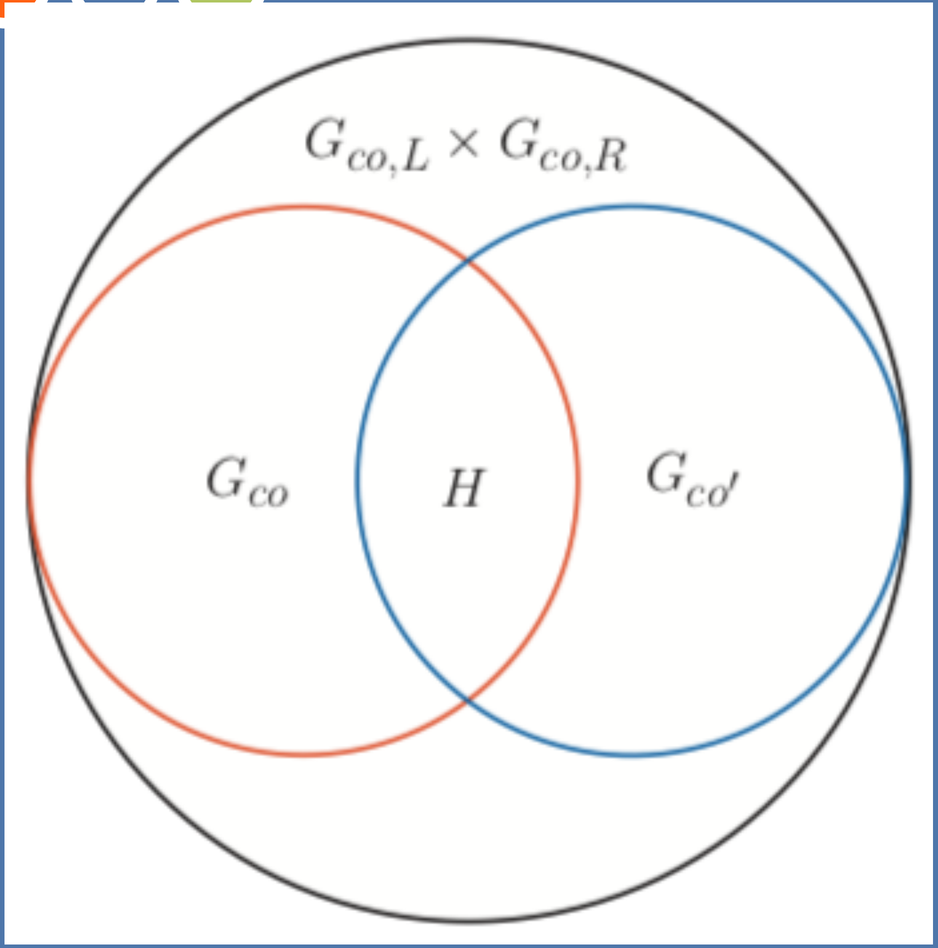


One free parameter except for f

Emergence of Maximal Symmetry

C. Csaki, T. Ma, J. Shu, J-H. Yu, arxiv:1810.07704

Why a maximal symmetry?



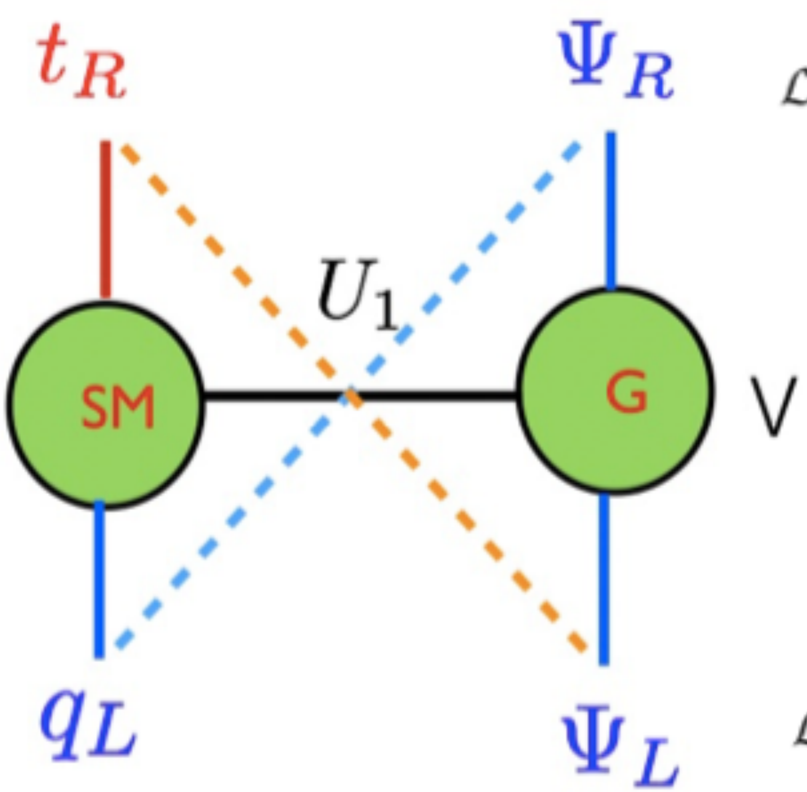
sounds like symmetry inflow

Ordinary case global symmetry breaks into H at the boundary

Maximal symmetry: global symmetry breaks into G_{V'} at the boundary

Integrating out the bulk from this boundary (composite) preserve this global symmetry and transmitted it to the other boundary (SM elecmentary)

How to realize a maximal symmetry?



Bulk femrion:

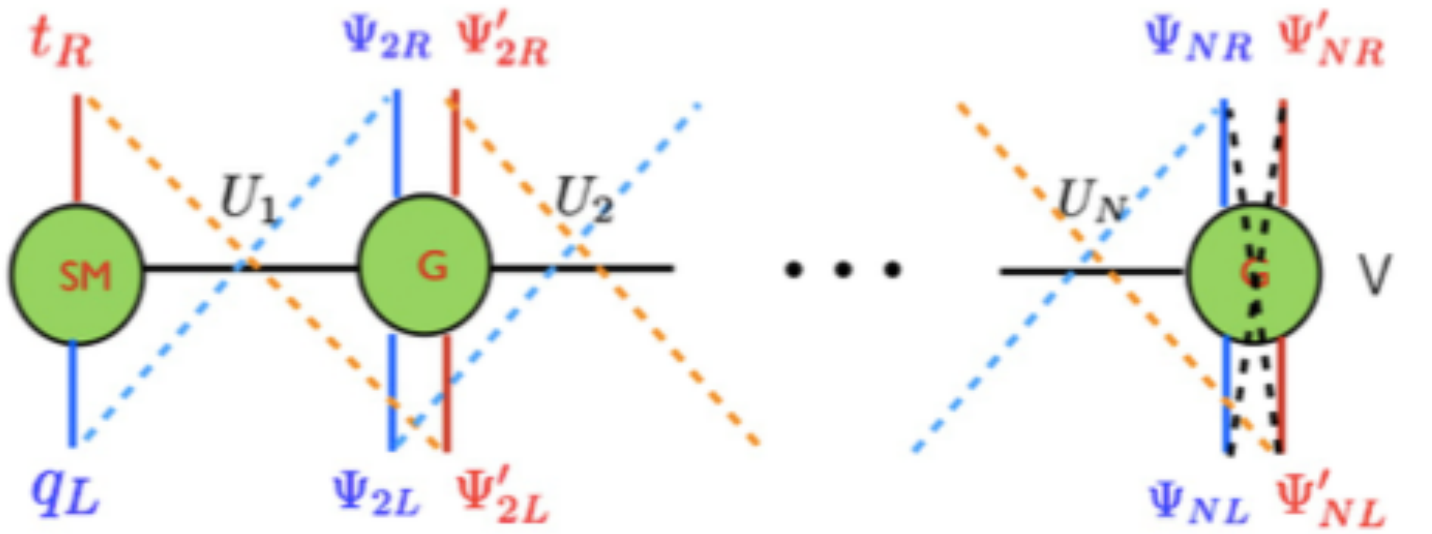
$$\mathcal{L}_{\rm eff} = \bar{\Psi}_{q_L} \not{p} (\Pi_0^L(p) + \Pi_1^L(p)\Sigma')\Psi_{q_L} - \bar{\Psi}_{q_L} M_1^t(p)\Sigma'\Psi_{t_R} + \bar{\Psi}_{t_R} \not{p} (\Pi_0^R(p) + \Pi_1^R(p)\Sigma')\Psi_{t_R} + h.c. \, , \quad (2)$$

Both LH & RH fields are in the fundamental representation

UV completion of two site moose

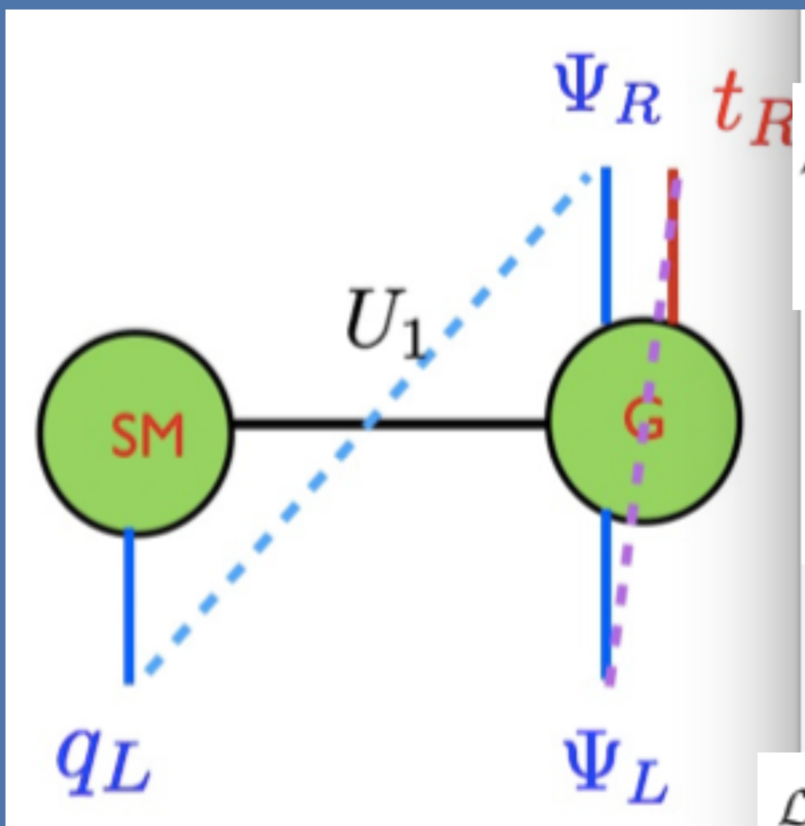
$$\mathcal{L}_f = \bar{q}_L i \not{D} q_L + \bar{\Psi} i \not{D} \Psi + \bar{t}_R i \not{D} t_R - \epsilon_L \bar{\Psi}_{q_L} U_1 \Psi_R - M \bar{\Psi}_L \Sigma \Psi_R - \epsilon_R \bar{\Psi}_L U_1^\dagger \Psi_{t_R} + h.c. \quad (5)$$

How to realize a maximal symmetry?



$$
\begin{aligned}
\mathcal{L}_f &= \bar{q}_L i \not{D} q_L + \bar{t}_R i \not{D} t_R + \sum_{i=2}^{N} (\bar{\Psi}_i i \not{D}_i \Psi_i) \\
&- \epsilon_1 \bar{\Psi}_{q_L} U_1 \Psi_{2R} - \sum_{j=2}^{N-1} \epsilon_j \bar{\Psi}_{jL} U_j \Psi_{j+1R} - M_i \sum_{i=2}^{N} \bar{\Psi}_{iL} \Psi_{iR} \\
&- \epsilon'_1 \bar{\Psi}_{t_R} U_1 \Psi'_{2L} - \sum_{j=2}^{N-1} \epsilon'_j \bar{\Psi}'_{jL} U_j \Psi'_{j+1R} - M'_i \sum_{i=2}^{N} \bar{\Psi}'_{iL} \Psi'_{iR} \\
&- M(\bar{\Psi}_{NL} \Sigma \Psi'_{NR} + \bar{\Psi}'_{NL} \Sigma \Psi_{NR}) + h.c. \qquad (11)
\end{aligned}
$$

Why a maximal symmetry?



Boundary fermion:

$$\mathcal{L}_{\text{eff}} = \bar{\Psi}_{q_L} \not{p} (\Pi_0^L(p) + \Pi_1^L(p)\Sigma')\Psi_{q_L} + \bar{\Psi}_{t_R} \not{p} \Pi_0^R(p) \Psi_{t_R} + \bar{\Psi}_{q_L} M_1^t(p) U \Psi_{t_R} + h.c. \quad (3)$$

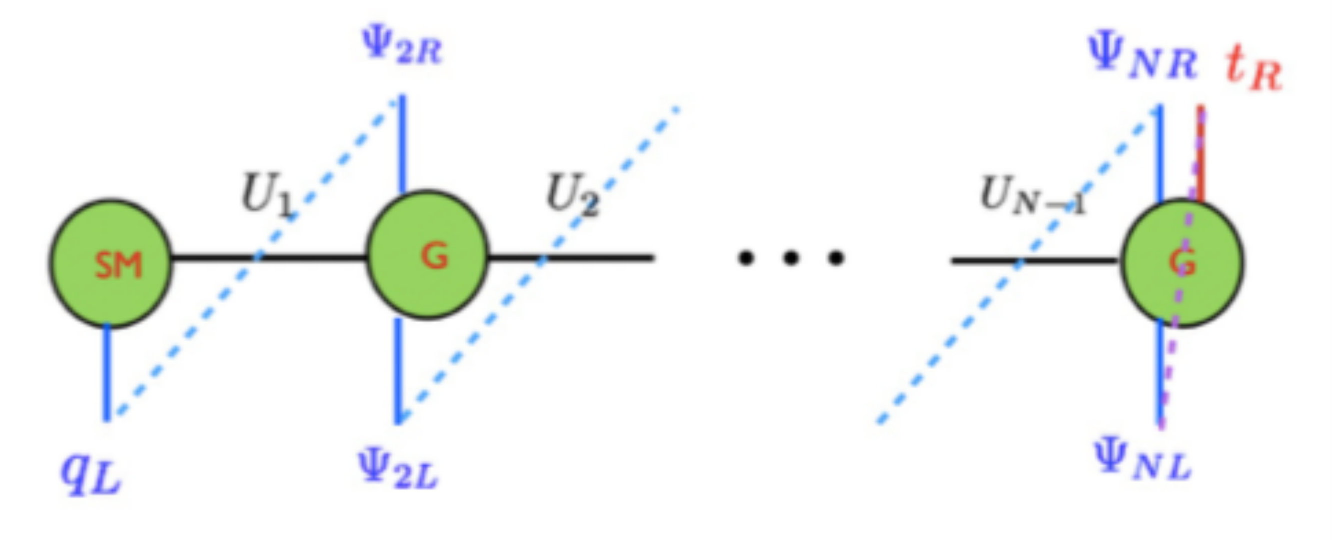
RH SM fermions are singlets

UV completion of two site moose

$$\mathcal{H} = U^\dagger \mathcal{V} \text{ with } \mathcal{V} = (0,0,0,0,1).$$

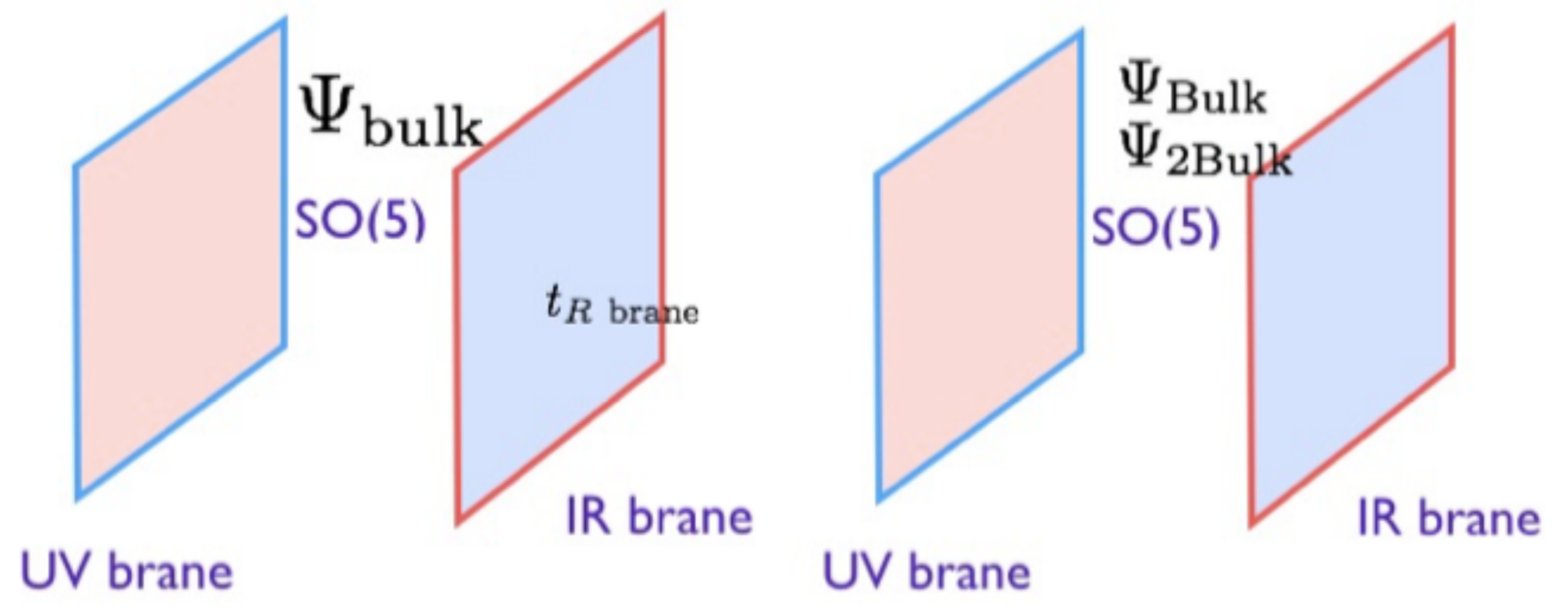
$$\mathcal{L}_f = \bar{q}_L i \not{D} q_L + \bar{\Psi} i \not{D} \Psi + \bar{t}_R i \not{D} t_R - \epsilon_L \bar{\Psi}_{q_L} U_1 \Psi_R - M \bar{\Psi}_L \Psi_R - \epsilon_R \bar{\Psi}_L \mathcal{H}' t_R + h.c. (6)$$

Why a maximal symmetry?



$$
\begin{aligned}
\mathcal{L}_f = & \ \bar{q}_L i \not{D} q_L + \sum_{i=2}^{N} \bar{\Psi}_i i \not{D}_i \Psi_i + \bar{t}_R i \not{D} t_R \\
& - \epsilon_1 \bar{\Psi}_{q_L} U_1 \Psi_{2R} - \sum_{j=2}^{N-1} \epsilon_j \bar{\Psi}_{jL} U_j \Psi_{j+1R} \\
& - \sum_{i=2}^{N} M_i \bar{\Psi}_{iL} \Psi_{iR} - \epsilon_N \bar{\Psi}_{NL} \mathcal{H}' t_R + h.c. \qquad (7)
\end{aligned}
$$

Extra dimension case:



$$U(R,R') = \text{Exp}\Big(i\frac{-\sqrt{2}\pi^{\hat{a}}T^{\hat{a}}}{f}\Big),$$

After integrating out the bulk

$$\begin{aligned}\mathcal{L}_{eff} &= \bar{\chi}'_L \not{p} \Pi_L(p) \chi'_L + \bar{t}_R \not{p} t_R \\ &+ (M(p) \bar{\chi}'_L \mathcal{H} t_R + h.c.)\end{aligned}$$

$$\begin{aligned}\mathcal{L}_H &= \bar{\chi}_L \not{p} \Pi^L(\tilde{m}) \chi_L - \bar{\psi}_R \not{p} \Pi^R(\tilde{m}) \psi_R \\ &+ M^{LR}(\bar{\chi}_L V \psi_R + \bar{\psi}_R V \chi_L),\end{aligned}$$

Comment

What I feel interesting or critical is that:

The boundary symmetry completely controls the bulk pNGB properties, in particular, the UV sensitivity of the pNGB Coleman- Weinberg potential

I wonder if there is a application in condense matter physics?

MS in the lattice can also be applied to low-dim condense matter system (Bilayer Quantum Hall System?)

Naturalness Sum rules

C. Csaki, F. Freitas, L. Huang, T. Ma, J. Shu, M. Perelstein, arxiv:1811.01961

Test and predictions

Top kinetic terms： no corrections from Higgs

$$M_t(h) \sim \sin\left(\frac{2h}{f}\right)\left(1+\frac{1}{2}\sin^2(h/f)\left(\Pi_1^q(0)-\Pi_1^t(0)\right)\right)$$

C. Csaki, T. Ma, J. Shu., 1702.00405
D. Liu, I. Low, C. Wagner, 1703.07791

However, the ggh coupling only scale with the derivative of the first part.

$$c_g = c_t$$

Maximal Symmetry limit

100 TeV perhaps tth 1%

M. Mangano, T Plehn, P. Reimitz, T. Schell, H-S. Shao, 1507.08169

Test and predictions

Find the top partner resonance (charge 2/3), sum rule of

diagonal Higgs Yukawa & mass

Mass eigenstates

C. Csaki, T. Ma, Phys.Rev.Lett. 119 (2017) no13, 1

C-R Chen, J. Hajer, T. Liu, I. Low, H. Zhang, JHEP 1709 (2017) 129

$$\mathrm{Tr}[Y_m M_D] = 0 + \mathcal{O}(v^2)$$

No quadratic div

$$\mathrm{Tr}[Y_m M_D^3] \;=\; 0 + \mathcal{O}(v^2/M_f^2)$$

No log div

C. Csaki, T. Ma, J. Shu., Phys.Rev.Lett. 119 (2017) no13, 131803

$$M_Q + M_S = 0$$

Lightest exotic charge (5/3)

Gauge Sum rules

Quadratic divergence

$$\mathrm{Tr}[g_{VVh}] = 0 + \mathcal{O}(\tilde{v}^2/f^2).$$

Log divergence

$$\mathrm{Tr}[g_{VVh} M_V^2] = 0 + \mathcal{O}(\tilde{v}^2/f^2),$$

SUSY Case

$$\mathrm{Tr}[g_{SSh}] - 2\mathrm{Tr}[Y_M M_D^\dagger + M_D Y_M^\dagger] + 3\mathrm{Tr}[g_{VVh}] = 0,$$

$$\mathrm{Tr}[g_{SSh}] - 4\mathrm{Tr}[Y_M M_D] + 3\mathrm{Tr}[g_{VVh}] = 0.$$

Quadratic divergence

Top sector/stop sector

$$\sum_i g_{\tilde{t}_i \tilde{t}_i h} - 4 y_t m_t = 0,$$

Gauge/gaugino/Higgs/Higgsino sector

$$4\sum_i (y_{C_i^+ C_i^- h} m_{C_i} + y_{N_i N_i h} m_{N_i}) - 3(g_{W^+W^-h} + g_{ZZh})$$
$$-\sum_i (g_{H_i^0 H_i^0 h} + g_{H_i^+ H_i^- h}) - g_{hhh} = 0$$

Non-SUSY Case: Collider

Non-susy case done with signs! See the talk tomorrow!

The build-in twin Higgs (Trigonometric Parity)

C. Csaki, T. Ma, J. Shu., Phys.Rev.Lett. 121 (2018) no23, 231801

Why twin Higgs?

Z. Chacko, H.-S. Goh, R. Harnik, Phys.Rev.Lett. 96 (2006) 231802

The key reason is that we still do not see the colored top partner yet!

Colored top partners are the most sensitive probe of composite Higgs models

Proved upper limit of lightest top partners for given symmetry breaking scale f

Light Higgs → Light Top Partners

D. Marzocca, M. Serone, J. Shu., JHEP 1208, 013 (2012)
O.Matsedonskyi, G. Panico, A. Wulzer, JHEP 1301, 164 (2013)

EW charged twin top almost have zero LHC bounds

Neutral Naturalness

See for instance

N. Craig, A.Katz, M.Strassler, R. Sundrum, JHEP 1507, 105 (2015)

Why composite twin Higgs?

Funny trigonometric parity $s_h \leftrightarrow c_h.$

M. Geller, O.Telem, PRL 114, 191801 (2015)

R. Barbieri, D. Greco, R. Rattazzi, A. Wulzer, JHEP 1508, 161 (2015)

M. Low, A. Tesi, L.T. Wang, PRD 91, 095012 (2015)

- Why Twin Higgs? Highly constrained by LEP
- The radiatively generated Higgs potential
- universal prediction on Higgs couplings (Like pion soft theorem)

If the strong dynamics triggers the breaking G/H, pNGB is a composite particle.

QCD chiral symmetry, pion

Trigonometric Parity as the build-in Twin Parity

However, the goldstone itself does have the spontaneous broken symmetry!

The symmetry of the G/H coset space manifold!

Inside any coset space manifold, there is a trigonometric parity

Physical higgs has a shift symmetry in the corresponding unbroken direction

$$\pi^i/f \to \pi^i/f + \epsilon^i.$$

Higgs parity: $\pi^i \to -\pi^i.$

C. Csaki, T. Ma, J. Shu., Phys.Rev.Lett. 121 (2018) no23, 231801

$$\frac{\pi^i}{f} \to -\frac{\pi^i}{f} + \frac{\pi}{2}$$

$U(1) \sim SO(2)$

$SO(N+1)/SO(N)$ $\quad S^N$

$$U = \begin{pmatrix} \mathbb{1}_3 & & & \\ & \cos\frac{h}{f} & & \sin\frac{h}{f} \\ & & 1 & \\ & -\sin\frac{h}{f} & & \cos\frac{h}{f} \end{pmatrix}.$$

Exchange of the 4th and 6th row

Adding matter fields

- The matter fields have to conserve such a build-in trigonometric parity

$$\Psi_{Q_L} = \frac{1}{\sqrt{2}} \begin{pmatrix} b_L \\ -ib_L \\ t_L \\ it_L \\ 0 \\ 0 \end{pmatrix} .$$

$$\Psi_{\tilde{t}_L} = \frac{1}{\sqrt{2}} \begin{pmatrix} 0 \\ 0 \\ 0 \\ 0 \\ \tilde{t}_L \\ i\tilde{t}_L \end{pmatrix} ,$$

Exchange the coordinates in the 3rd and 5th, 4th and 6th row

$$P = P_0 P_1^h = \begin{pmatrix} 1 & & & & & \\ & 1 & & & & \\ & & & & 1 & \\ & & & & & 1 \\ & & 1 & & & \\ & & & 1 & & \end{pmatrix}$$

$$P_1^h = \begin{pmatrix} \mathbb{1}_3 & & & \\ & & & 1 \\ & & 1 & \\ & 1 & & \end{pmatrix} .$$

$$y_t = \tilde{y}_t$$

$$\Psi_{Q_L} \leftrightarrow P\Psi_{\tilde{t}_L}, \quad t_R \leftrightarrow \tilde{t}_R, \quad \Sigma \to P\Sigma$$

Fermion Lag

The top and bottom sector

$$\begin{aligned}\mathcal{L}^t_{eff} &= \bar{b}_L \not{p} \Pi^q_0(p) b_L + \bar{t}_L \not{p}(\Pi^q_0(p) + \Pi^q_1(p) c_h^2) t_L \\ &+ \bar{t}_R \not{p} \Pi^t_0(p) t_R + \bar{\tilde{t}}_L \not{p}(\Pi^q_0(p) + \Pi^q_1(p) s_h^2) \tilde{t}_L \\ &+ \bar{\tilde{t}}_R \not{p} \Pi^t_0(p) \tilde{t}_R - \frac{i M^t_1(p)}{\sqrt{2}} (\bar{t}_L t_R s_h + \bar{\tilde{t}}_L \tilde{t}_R c_h) + h.c.\end{aligned}$$

A UV Completion

$$SO(6)/SO(5) \simeq SU(4)/Sp(4)$$

The latter has the fermion condensation

	$Sp(2N)$	$SU(2)_L$	$U(1)_Y$	$SU(3)_c$	$U(1)_\eta$
(ψ_1, ψ_2)	$\square$	$\square$	$\mathbf{0}$	$\mathbf{1}$	$\mathbf{1}$
ψ_3	$\square$	$\mathbf{1}$	$-\frac{1}{2}$	$\mathbf{1}$	-1
ψ_4	$\square$	$\mathbf{1}$	$\frac{1}{2}$	$\mathbf{1}$	-1

Gauge sector automatically satisfy the Weinberg sum rule
Lowest chiral breaking operators at UV: 4-fermions dim 6.

SU(4)/Sp(4) matter content

$$\Psi_{Q_L} = \frac{1}{\sqrt{2}} \begin{pmatrix} \mathbf{0} & Q \\ -Q^T & \mathbf{0} \end{pmatrix} \text{ and } \Psi_{\tilde{t}_L} = \frac{1}{\sqrt{2}} \begin{pmatrix} i\tilde{t}_L\sigma^2 & 0 \\ 0 & \mathbf{0} \end{pmatrix}$$

$$U = \begin{pmatrix} c'\mathbb{1}_2 & i\sigma^2 h s' \\ i\sigma^2 h s' & c'\mathbb{1}_2 \end{pmatrix}$$

$$\eta \;:\; i(\psi_1\psi_2 + \psi_3\psi_4 - \psi_1^c\psi_2^c - \psi_3^c\psi_4^c)$$

$$\begin{aligned} \mathcal{L}^t_{eff} = \; & \bar{b}_L \not{p} \Pi^q_0(p) b_L + \bar{t}_L \not{p} (\Pi^q_0(p) - 2\Pi^q_1(p) s_h^2) t_L \\ & + \bar{t}_R \not{p} \Pi^t_0(p) t_R + \bar{\tilde{t}}_R \not{p} \Pi^t_0(p) \tilde{t}_R \\ & + \bar{\tilde{t}}_L \not{p} (\Pi^q_0(p) - 2\Pi^q_1(p) c_h^2) \tilde{t}_L \\ & - \sqrt{2} M^t_1(p) \left(\bar{t}_L t_R s_h + \bar{\tilde{t}}_L \tilde{t}_R c_h \right) + h.c. \qquad (36) \end{aligned}$$

Extension for Composite Top

	$Sp(2N)$	$SU(2)_L$	$U(1)_Y$	$SU(3)_c$	$SU(3)'_c$
χ_L	$\begin{smallmatrix}\square\\\square\end{smallmatrix}$	$\mathbf{1}$	$\frac{2}{3}$	$\square$	$\mathbf{1}$
χ_R^c	$\begin{smallmatrix}\square\\\square\end{smallmatrix}$	$\mathbf{1}$	$-\frac{2}{3}$	$\bar{\square}$	$\mathbf{1}$
$\tilde{\chi}_L$	$\begin{smallmatrix}\square\\\square\end{smallmatrix}$	$\mathbf{1}$	$\mathbf{1}$	$\mathbf{1}$	$\square$
$\tilde{\chi}_R^c$	$\begin{smallmatrix}\square\\\square\end{smallmatrix}$	$\mathbf{1}$	$\mathbf{1}$	$\mathbf{1}$	$\bar{\square}$

	$SU(4) \times SU(12)$	$Sp(4) \times SO(12)$
$\chi(\psi\psi)$	$(\mathbf{6}, \mathbf{12})$	$(\mathbf{5}, \mathbf{12})$, $(\mathbf{1}, \mathbf{12})$
$\chi(\psi^c\psi^c)$	$(\mathbf{6}, \mathbf{12})$	$(\mathbf{5}, \mathbf{12})$, $(\mathbf{1}, \mathbf{12})$
$\psi(\chi\psi)$	$(\mathbf{10}, \mathbf{12})$	$(\mathbf{10}, \mathbf{12})$
$\psi(\chi^c\psi^c)$	$(\mathbf{1}, \overline{\mathbf{12}})$	$(\mathbf{1}, \mathbf{12})$
$\psi(\chi^c\psi^c)$	$(\mathbf{15}, \overline{\mathbf{12}})$	$(\mathbf{15}, \mathbf{12})$

Extension for Composite Top

$$\mathcal{L} = f\bar{\Psi}_L U(\epsilon_{5L}\Psi_{5R} + \epsilon_{1L}\Psi_{1R}) + f\epsilon_R\bar{\Psi}_R\Psi_{1L} + M_5\bar{\Psi}_{5L}\Psi_{5R} + M_1\bar{\Psi}_{1L}\Psi_{1R} + h.c,$$

$$\Psi_Q = \begin{pmatrix} iB - iX_{5/3} \\ B + X_{5/3} \\ T + X_{2/3} \\ -T + X_{2/3} \\ iT'_+ - iT'_- \\ 0 \end{pmatrix} \qquad \Psi_S = \begin{pmatrix} 0 \\ 0 \\ 0 \\ 0 \\ 0 \\ T'_+ + T'_- \end{pmatrix}$$

$$\tilde{\Psi}_Q = \begin{pmatrix} i\tilde{B}_{-1} - i\tilde{X}_1 \\ \tilde{B}_{-1} + \tilde{X}_1 \\ \tilde{T}_0 + \tilde{X}_0 \\ -\tilde{T}_0 + \tilde{X}_0 \\ i\tilde{T}'_+ - i\tilde{T}'_- \\ 0 \end{pmatrix} \qquad \tilde{\Psi}_S = \begin{pmatrix} 0 \\ 0 \\ 0 \\ 0 \\ 0 \\ \tilde{T}'_+ + \tilde{T}'_- \end{pmatrix}$$

Higgs potential

$$V_g = \gamma_g s_h^2 \quad V_f = \gamma_f(-s_h^2 + s_h^4),$$

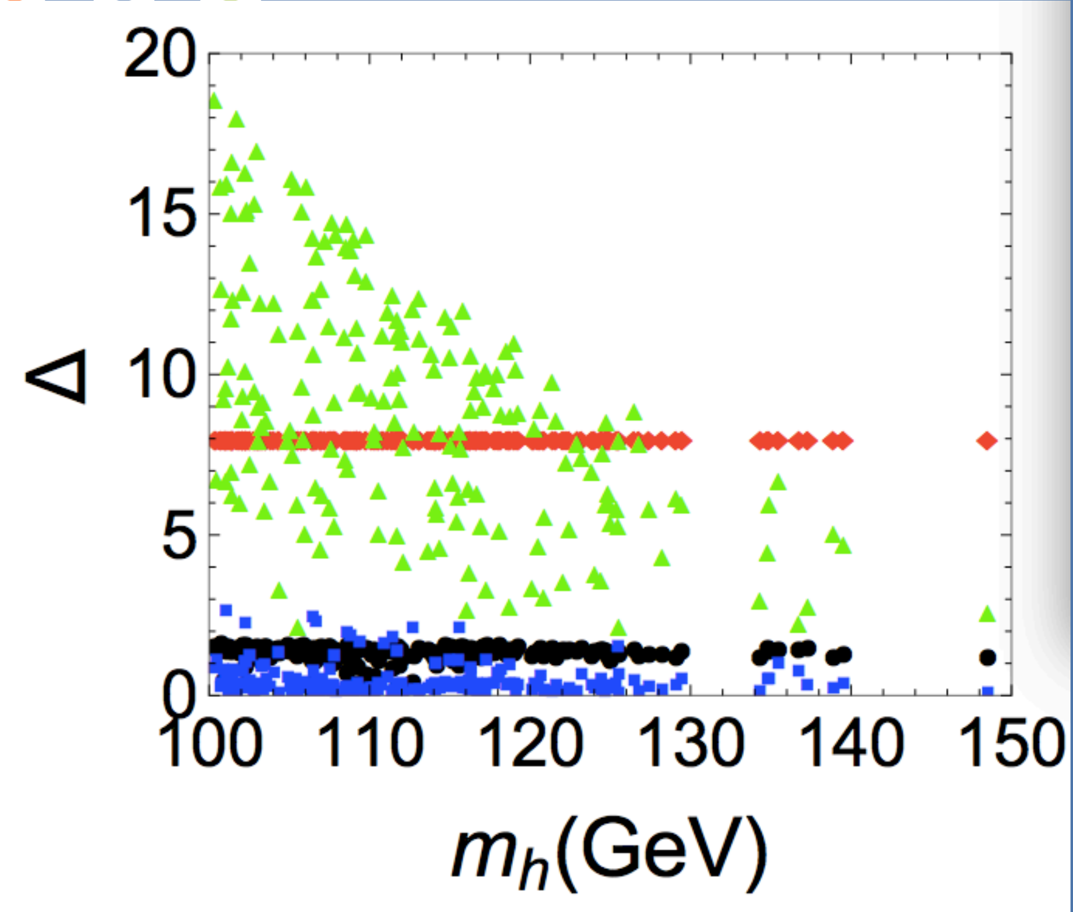
$$V = V_g + V_f = -\gamma s_h^2 + \beta s_h^4,$$

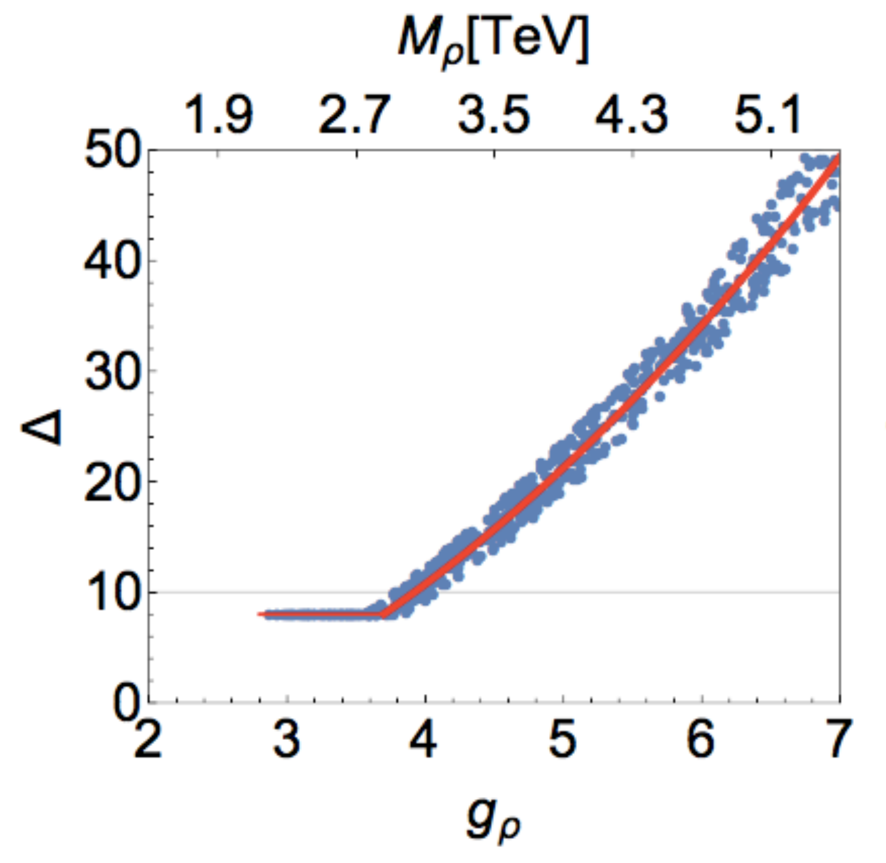
$$\gamma = \gamma_f - \gamma_g \text{ and } \beta = \gamma_f$$

$$V_f \simeq c' \frac{N_c M_f^4}{16\pi^2} \left(\frac{y_t}{g_f}\right)^4 [-s_h^2 + s_h^4]$$
$$\simeq c' \frac{N_c f^4}{16\pi^2} y_t^4 [-s_h^2 + s_h^4],$$

Notice top Yukawa 4th power

Higgs potential





Novel six top signals

$$t' \to B'_\mu\, t \to t\, \bar{t}\, t.$$

Completely new and novel channels

H-Y. Han, L. Huang, T. Ma, J. Shu, T. Tait, Y.C. Wu, arxiv:1812.11286

Future Prospects

- Understanding models of EWSB (real progress after 2000)
- EFT approach to EWSB, connect collider physics with true natural of EWSB
- Theoretical Framework can be applied to many other aspects? (Inflation, axion, condensed matter?)

Backup
slice

Discreet Parities

Hidden additional Z_2 forbids the tuning term: (like composite twin Higgs)

M. Geller, O.Telem, PRL 114, 191801 (2015)

R. Barbieri, D. Greco, R. Rattazzi, A. Wulzer, JHEP 1508, 161 (2015)

M. Low, A. Tesi, L.T. Wang, PRD 91, 095012 (2015)

$s_h \Leftrightarrow -c_h$ in the Higgs potential

Can be realized under the following transformation

$$\begin{aligned} \Psi_{+L} &\rightarrow P_1\Psi_{+L},\ \Psi_{+R} \rightarrow VP_1V\Psi_{+R},\ U \rightarrow VUVP_1V, \\ \Psi_{q_L} &\rightarrow V\Psi_{q_L} = \Psi_{q_L},\ \Psi_{t_R} \rightarrow P_2\Psi_{t_R} = \Psi_{t_R} \end{aligned} \tag{28}$$

$$P_1 = \mathrm{diag}(1_{3\times3}, \sigma_1), P_2 = \mathrm{diag}(1_{3\times3}, -\sigma_3).$$

Vector bosons

SO(5)/SO(4)

Consider one vector meson and one axi-vector meson

$$\rho_\mu \equiv \mathbf{6} \qquad a_\mu \equiv \mathbf{4}$$

$$\rho_\mu \to h\rho_\mu h^\dagger + \frac{i}{g_\rho} h\partial_\mu h^\dagger$$
$$a_\mu \to h a_\mu h^\dagger$$

The Lag based on HLS

$$\mathcal{L}^v = -\frac{1}{4}\,\mathrm{Tr}[\rho_{\mu\nu}\rho^{\mu\nu}] + \frac{f_\rho^2}{2}\mathrm{Tr}[(g_\rho \rho_\mu - E_\mu)^2]$$
$$\mathcal{L}^a = -\frac{1}{4}\,\mathrm{Tr}[a_{\mu\nu}a^{\mu\nu}] + \frac{f_a^2}{2\Delta^2}\mathrm{Tr}[(g_a a_\mu - \Delta d_\mu)^2]$$
$$\mathcal{L}_{\mathrm{kin}} = \frac{f^2}{4}\mathrm{Tr}[d_\mu d^\mu] \qquad (3)$$

$$\rho_{\mu\nu} = \partial_\mu \rho_\nu - \partial_\nu \rho_\mu - i g_\rho [\rho_\mu, \rho_\nu],$$
$$a_{\mu\nu} = \Delta_\mu a_\nu - \Delta_\nu a_\mu, \qquad \Delta = \partial - iE.$$

$$m_\rho^2 = g_\rho^2 f_\rho^2 \qquad m_a^2 = \frac{g_a^2 f_a^2}{\Delta^2}$$

Δ is a free parameter

Vector bosons

Further simplified as

$$\mathcal{L} = \frac{f^2 + 2f_a^2}{4}\mathrm{Tr}[d_\mu d^\mu] - m_a f_a \mathrm{Tr}[a_\mu(E_\mu + d_\mu)] + \frac{g_a^2 f_a^2}{2\Delta^2}\mathrm{Tr}[a_\mu a^\mu]$$
$$+\frac{f_\rho^2}{2}\mathrm{Tr}[E_\mu E^\mu] - m_\rho f_\rho \mathrm{Tr}[\rho_\mu(E_\mu + d_\mu)] + \frac{g_\rho^2 f_\rho^2}{2}\mathrm{Tr}[\rho_\mu \rho^\mu] \quad (7)$$

For symmetric coset space, G-invariant building blocks

$$\rho_\mu \pm a_\mu \qquad E_\mu \pm d_\mu$$

$$\mathcal{L} = f_+^2 \mathrm{Tr}[(d_\mu + E_\mu)^2] + f_-^2 \mathrm{Tr}[V(E_\mu + d_\mu)V(E^\mu + d_\mu)]$$
$$- m_+^2 \mathrm{Tr}[(\rho_\mu + a_\mu)(d_\mu + E_\mu)] - m_-^2 \mathrm{Tr}[V(\rho_\mu + a_\mu)V(d_\mu + E_\mu)]$$
$$+ \frac{m_\rho^2 + m_a^2}{4}\mathrm{Tr}[(\rho_\mu + a_\mu)(\rho_\mu + a_\mu)]$$
$$+ \frac{m_\rho^2 - m_a^2}{4}\mathrm{Tr}[V(\rho_\mu + a_\mu)V(\rho_\mu + a_\mu)] \quad (8)$$

$$f_+^2 = \frac{f^2+2f_a^2+2f_\rho^2}{8},$$

$$m_+^2 = \frac{m_\rho f_\rho + m_a f_a}{2}, \quad m_-^2 = \frac{m_\rho f_\rho - m_a f_a}{2}$$

$$f_-^2 = \frac{f^2+2f_a^2-2f_\rho^2}{8}$$

Vector bosons

Again, theory is made of one G-invariant adjoints for one G and also V

$SO(5)_1$ $U^\dagger D_\mu U \to \Omega_1 U^\dagger D_\mu U \Omega_1^\dagger$ Higgs shift sym lies in $[SO(5)/SO(4)]_1$

$SO(5)_2$ $\rho_\mu + a_\mu \to \Omega_2(\rho_\mu + a_\mu)\Omega_2^\dagger$

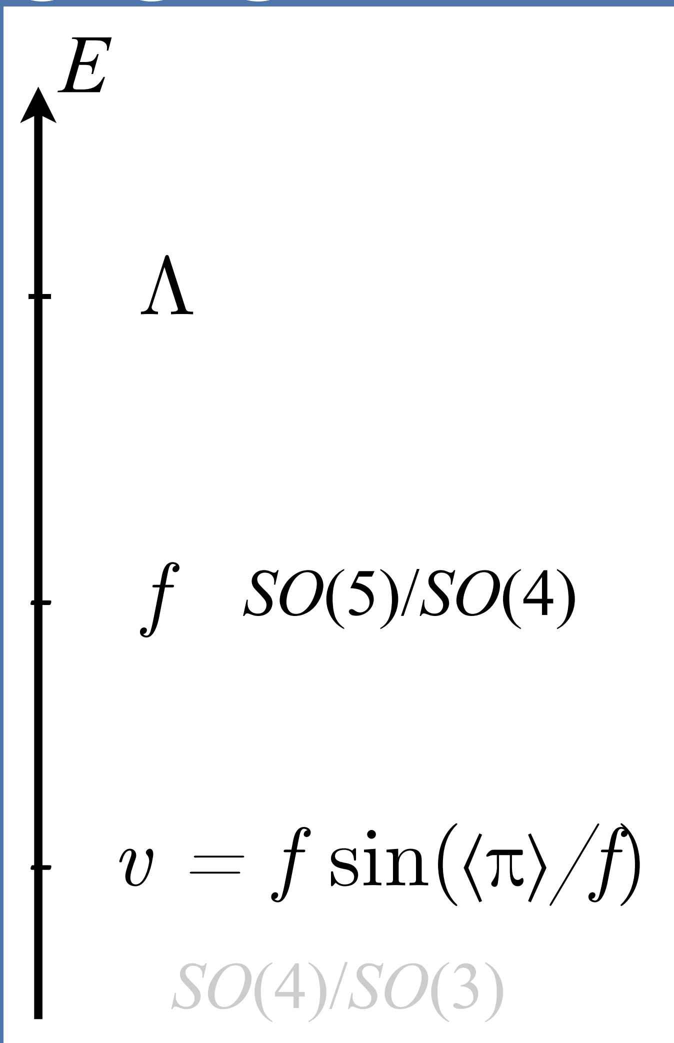
Automatically get the Weinberg sum rules

CYB in the 1st line $V_g \sim g_0^2 f_-^2 \Lambda^2$ — $f_- = 0$ 1st WS

CYB in the 2nd line $V_g \sim g_0^2 m_+^2 m_-^2 \log\Lambda^2$ — $m_- = 0$ 2nd WS

CYB in the 3rd line $V_g \sim g_0^2 m_+^4 (m_\rho^2 - m_a^2)/\Lambda^2$ — $m_\rho \approx m_a$

Higgs as pNGB



Consider the minimal group G/H

$$SO(5)\times U(1)_X \to SO(4)\times U(1)_X$$

K. Agashe, R. Contino, A. Pomarol, NPB 719 (2005) 165

at the scale f > v $\xi \equiv \frac{v^2}{f^2}$

There are four NGBs: $\pi^{\hat{a}}$, with $\hat{a} = 1,2,3,4$.

They transform as a 4 of $SO(4)$

(2,2) of $SU(2)$ x $SU(2)$ ~ $SO(4)$.

$$Y = T_{3R} + X$$

$SU(2)_L \times U(1)_Y \subset SU(2)_L \times SU(2)_R \times U(1)_X \sim SO(4)' \times U(1)_X$

See other holographic models based on SU(3)/SU(2)

R. Contino, Y. Nomura, A. Pomarol, NPB 671 (2003) 148

CCWZ of GCHM

pNGB matrix:

$$U = \exp\left(i\frac{\sqrt{2}}{f}h^{\hat{a}}T^{\hat{a}}\right).$$

$$\hat{a} = 1, 2, 3, 4.$$

The CCWZ transformation

C.G. Callan, S.R. Coleman, J.Wess, B. Zumino, PR 177 (1969) 2247

$$U \to gUh(h^{\hat{a}}, g)^{\dagger}$$

$$iU^{\dagger}D_{\mu}U = \hat{d}^{\hat{a}}_{\mu}T^{\hat{a}} + \hat{E}_{\mu}T^{a}$$

SM gauge fields

Leading order chiral Lag

$$\mathcal{L}_{\sigma_g} = -\frac{1}{4}W^{aL}_{\mu\nu}W^{aL\mu\nu} - \frac{1}{4}B_{\mu\nu}B^{\mu\nu} + \frac{f^2}{4}\mathrm{Tr}\left(\hat{d}_{\mu}\hat{d}^{\mu}\right)$$

CCWZ of GCHM

$$iU^\dagger D_\mu U = \hat{d}_\mu^{\hat{a}} T^{\hat{a}} + \hat{E}_\mu T^a$$

SM gauged

$$\hat{d}_\mu = \quad -\frac{\sqrt{2}}{f}(D_\mu h) + \ldots$$

$$\hat{E}_\mu = \quad g_0 A_\mu + \frac{i}{f^2}(h \overleftrightarrow{D}_\mu h) + \ldots$$

Transform like a gauge field

$$m_W = \frac{gf}{2}\sin\frac{\langle h\rangle}{f} \equiv \frac{gv}{2}$$

$$s_h = \sin\frac{\langle h\rangle}{f}, \qquad \xi \equiv s_h^2$$

Higgs physics

$$f^2 \sin^2 \frac{h}{f} = f^2 \left[\sin^2 \frac{\langle h \rangle}{f} + 2 \sin \frac{\langle h \rangle}{f} \cos \frac{\langle h \rangle}{f} \left(\frac{h}{f} \right) + \left(1 - 2 \sin^2 \frac{\langle h \rangle}{f} \right) \left(\frac{h}{f} \right)^2 + \ldots \right]$$

$$= v^2 + 2v\sqrt{1-\xi}\, h + (1 - 2\xi)\, h^2 + \ldots$$

W boson mass

modification of hVV coupling

$$a = \sqrt{1-\xi} \qquad b = 1 - 2\xi$$

Similarly for fermions.

$$m_f(h) \propto \sin\left(\frac{2h}{f}\right) \qquad c = \frac{1-2\xi}{\sqrt{1-\xi}}$$

5, 10

$$m_f(h) \propto \sin\left(\frac{h}{f}\right) \qquad c = \sqrt{1-\xi}$$

Spinorial 4

电弱对称破缺机制

Higgs 势能:　　　　辐射修正

$$V_f(h) \simeq -\gamma_f s_h^2 + \beta_f s_h^4,$$

$$\sin^2\langle H\rangle/f = \xi \ll 1$$

$$m_H^2 = 8\,\xi(1-\xi)\,\beta\,.$$

$$\gamma_g = -\frac{3}{8(4\pi)^2}\int_0^\infty dp_E^2\, p_E^2 \left(\frac{3}{\Pi_0} + \frac{c_X^2}{\Pi_B}\right)\Pi_1,$$
$$\beta_g = -\frac{3}{64(4\pi)^2}\int_{\mu_g^2}^\infty dp_E^2\, p_E^2 \left(\frac{2}{\Pi_0^2} + \left(\frac{1}{\Pi_0} + \frac{c_X^2}{\Pi_B}\right)^2\right)\Pi_1^2.$$

规范波色子贡献

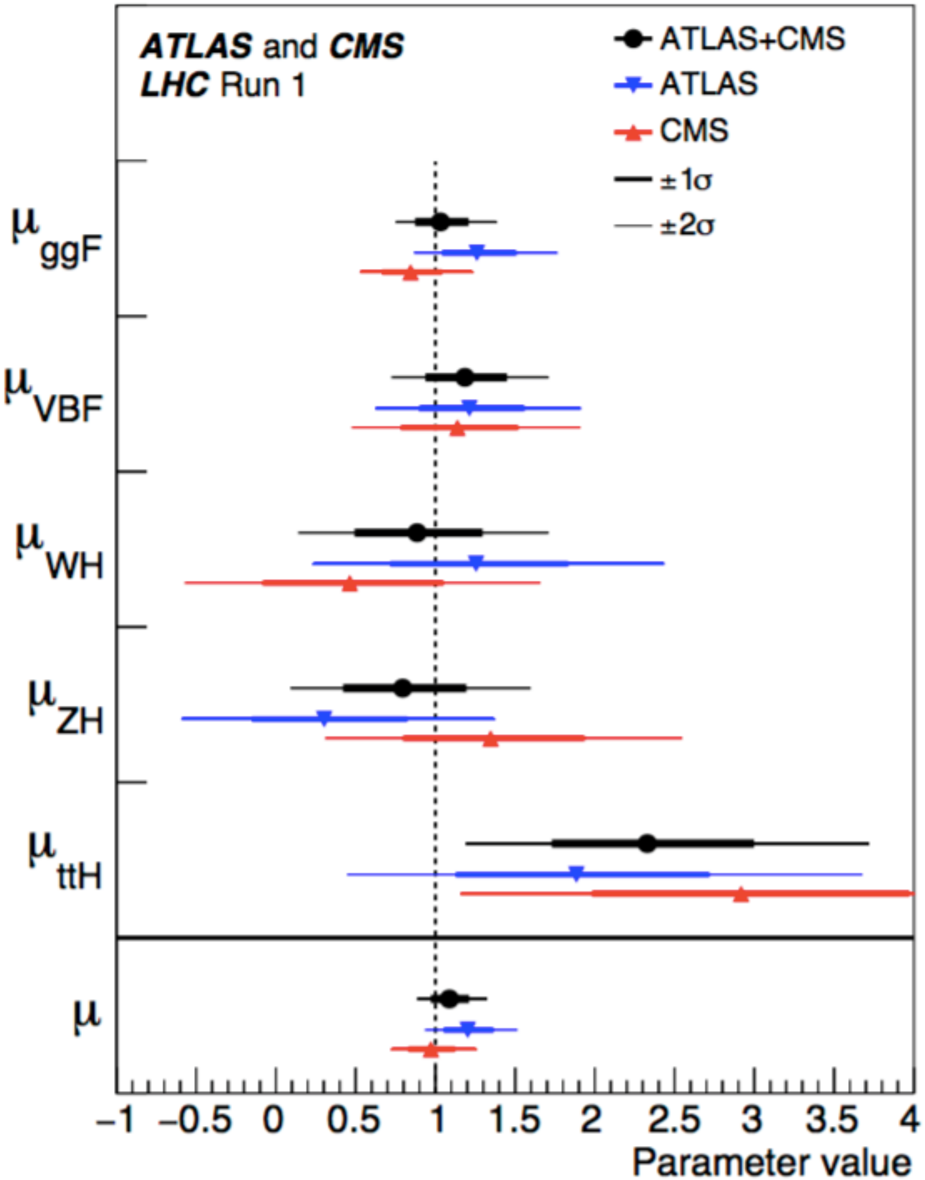
$$\gamma_f = \frac{2N_c}{(4\pi)^2}\int_0^\infty dp_E^2\, p_E^2 \left(\frac{\Pi_{1Q}}{\Pi_Q} + \frac{\Pi_{1S}}{\Pi_S} + \frac{\Pi_{QS}^2}{p_E^2\Pi_Q\Pi_S}\right),$$
$$\beta_f = \frac{N_c}{(4\pi)^2}\int_{\mu_f^2}^\infty dp_E^2\, p_E^2 \left(\left(\frac{\Pi_{QS}^2}{p_E^2\Pi_Q\Pi_S} + \frac{\Pi_{1Q}}{\Pi_Q} + \frac{\Pi_{1S}}{\Pi_S}\right)^2 - \frac{2(p_E^2\Pi_{1Q}\Pi_{1S} - \Pi_{QS}^2)}{p_E^2\Pi_Q\Pi_S}\right).$$

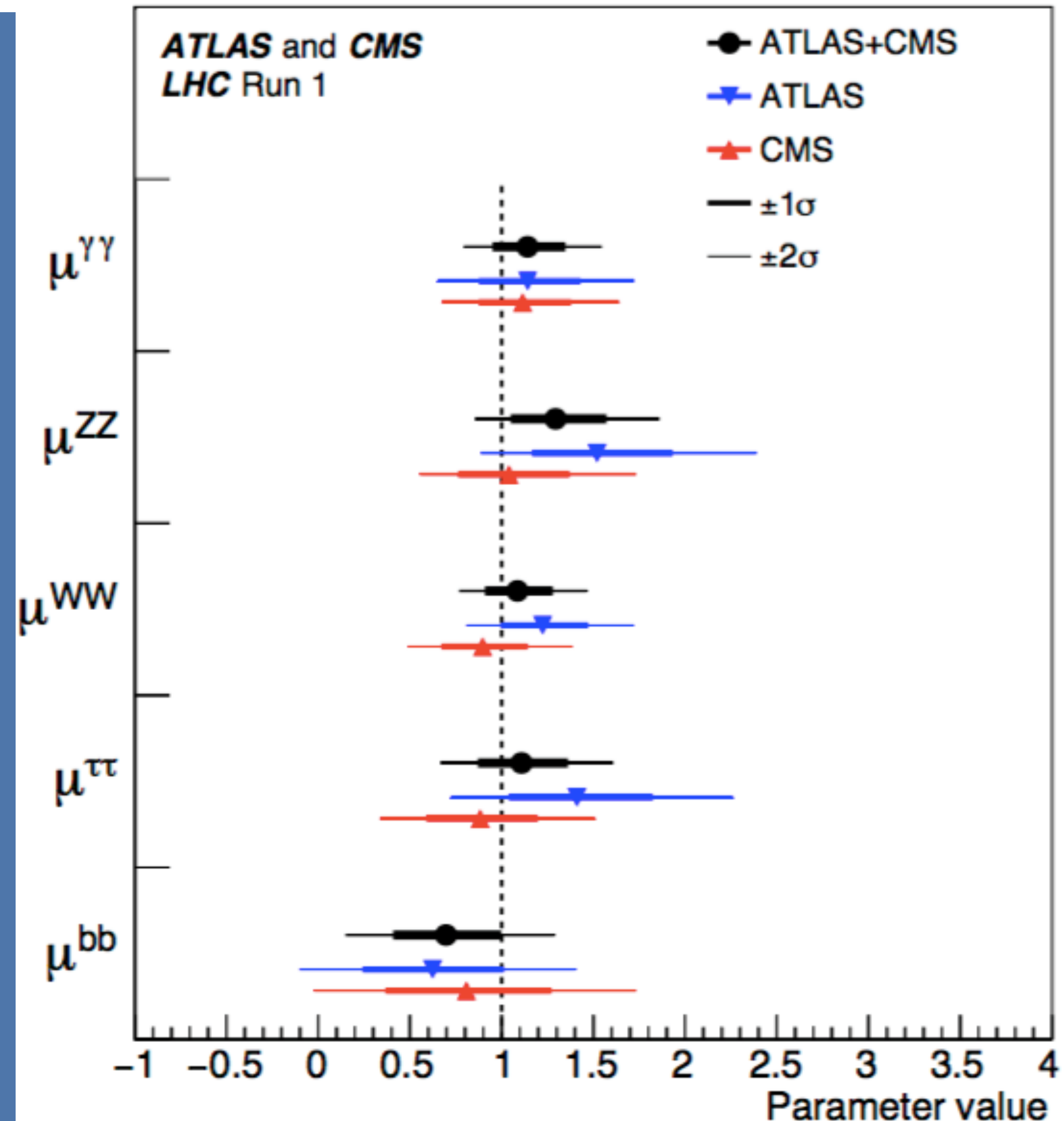
费米子贡献

$$M_t^2(q^2,\langle h\rangle) = \frac{\left|\Pi_{t_L t_R}\left(q^2,\langle h\rangle\right)\right|}{\sqrt{\Pi_{t_L}\left(q^2,\langle h\rangle\right)\Pi_{t_R}\left(q^2,\langle h\rangle\right)}}.$$

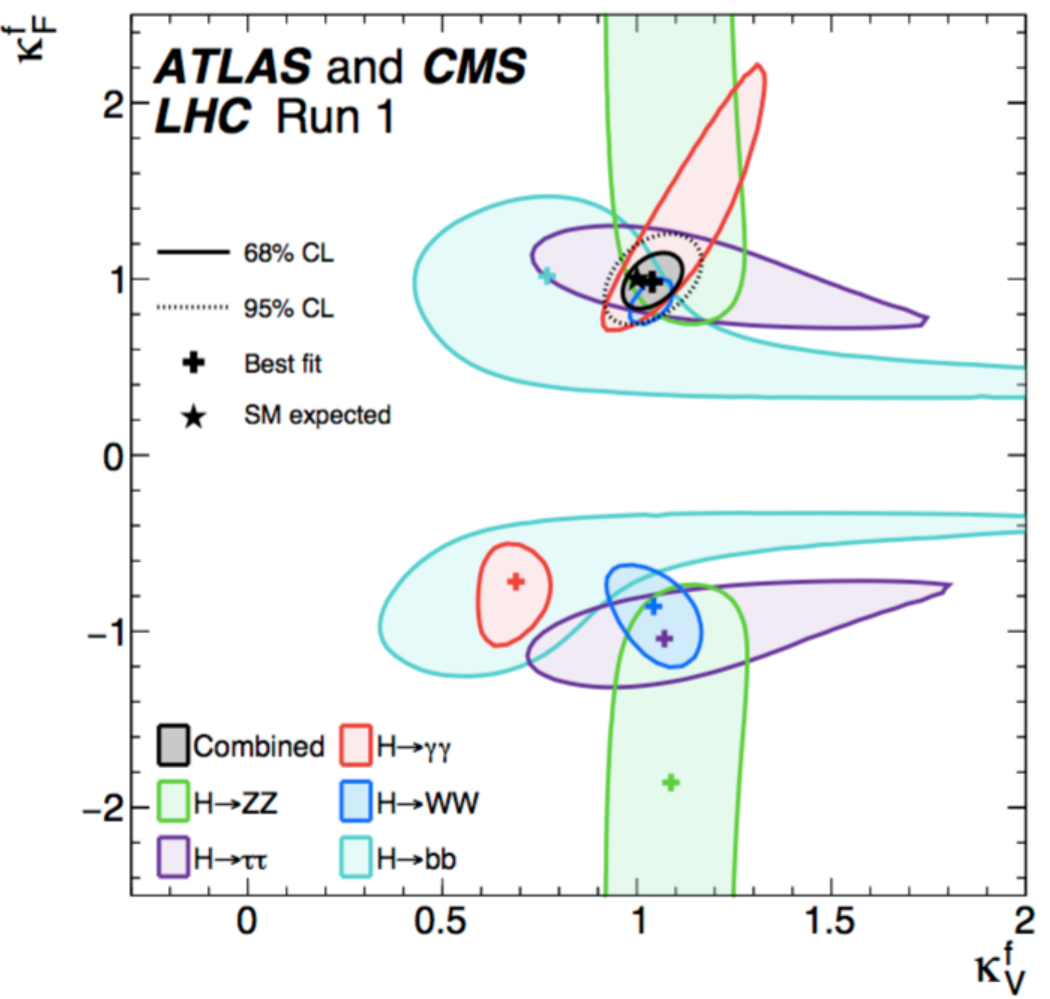
Top 夸克质量

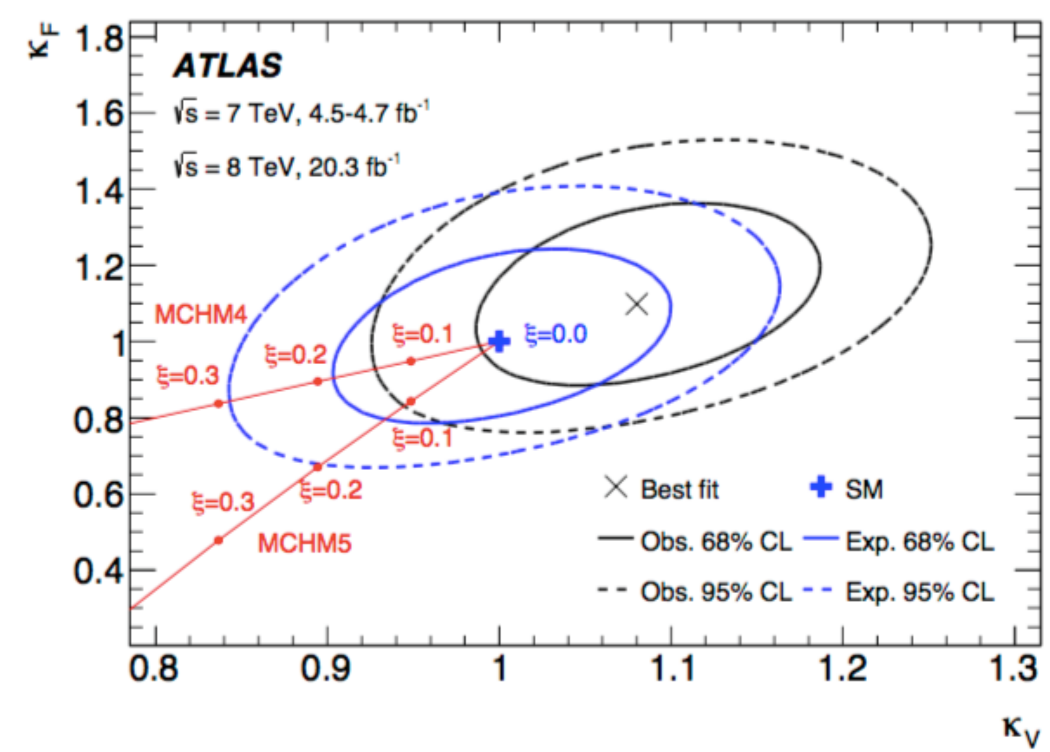
Higgs产生和衰变


ATLAS and CMS
LHC Run 1
ATLAS+CMS
ATLAS
CMS
±1σ
±2σ
μ_{ggF}
μ_{VBF}
μ_{WH}
μ_{ZH}
μ_{ttH}
μ
−1 −0.5 0 0.5 1 1.5 2 2.5 3 3.5 4
Parameter value


ATLAS and CMS
LHC Run 1
ATLAS+CMS
ATLAS
CMS
±1σ
±2σ
$\mu^{\gamma\gamma}$
μ^{ZZ}
μ^{WW}
$\mu^{\tau\tau}$
μ^{bb}
−1 −0.5 0 0.5 1 1.5 2 2.5 3 3.5 4
Parameter value

Higgs物理





Top耦合为负的情况不再存在

Higgs 拟合 $\xi < 0.1$