BSM from Higgs precision physics

Kei Yagyu

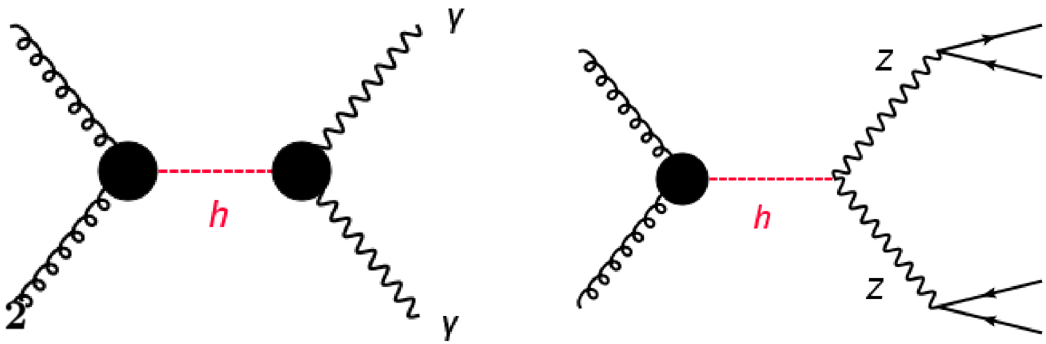
Seikei U

Higgs Couplings

2018, 30th November, Tokyo

Introduction

- 2012: Higgs discovery
- 2012: Gauge coupling



No doubt for existence of at least one Higgs doublet

Establish the Standard Model for Particle Physics!

- 2018: b and t Yukawa

$$y_t \bar{Q}_L \tilde{\Phi} t_R + y_b \bar{Q}_L \Phi b_R + y_\tau \bar{L}_L \Phi \tau_R$$

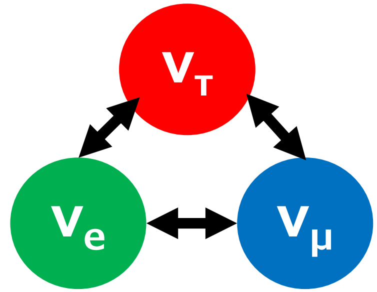
Is this the **END** of the story?

Of course, **NO!!**

… otherwise, we may loose the job.

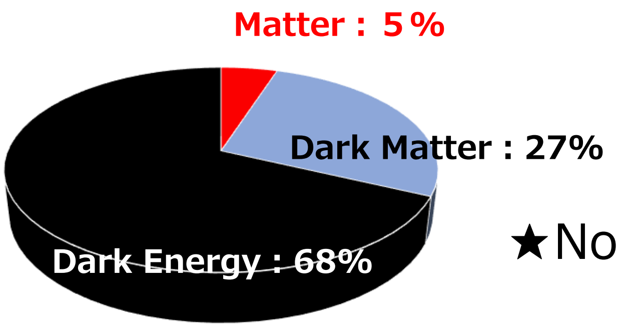
BSM: Phenomena

- Neutrino oscillation



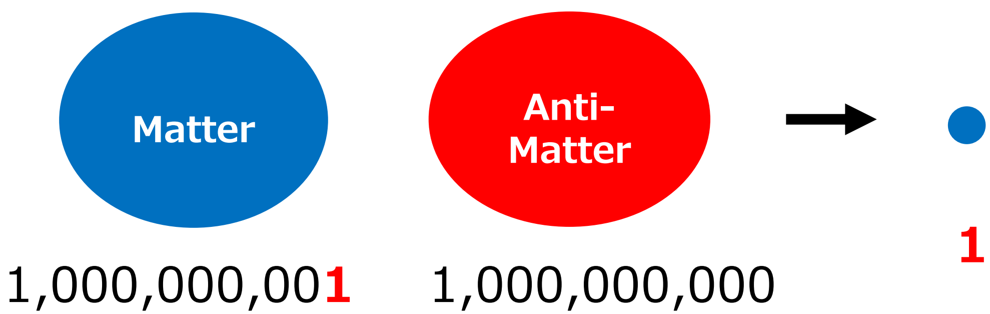
★Massless ν in the SM

- Dark matter/energy



★No neutral, stable and massive particle in the SM

- Baryon asymmetry



★Not enough CPV in the SM

BSM: Unification

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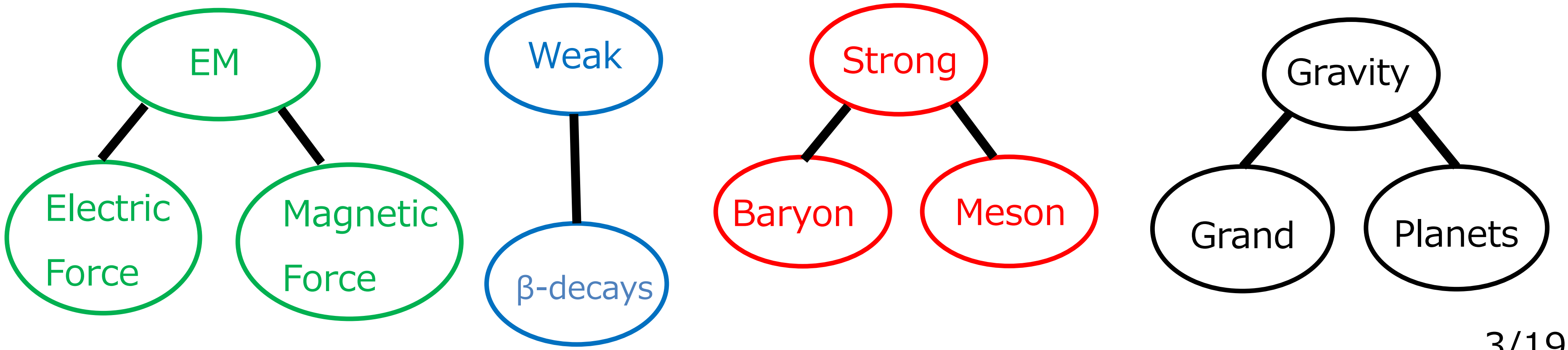
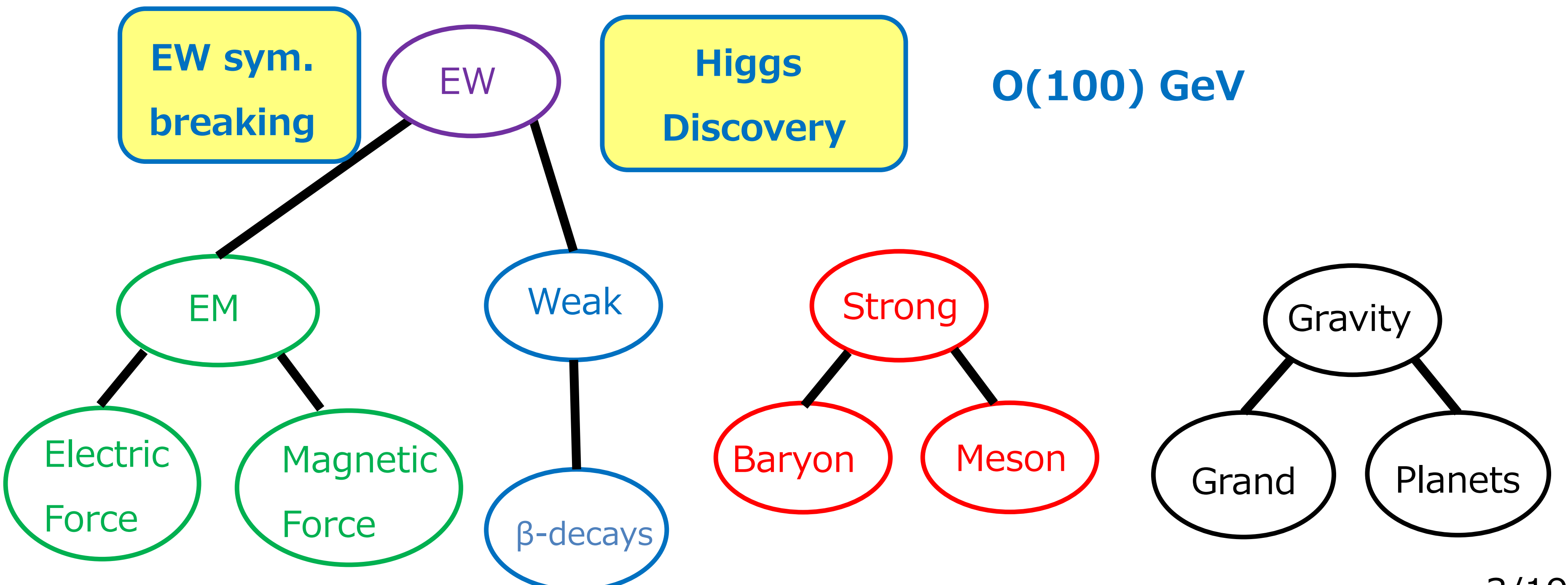


BSM: Unification



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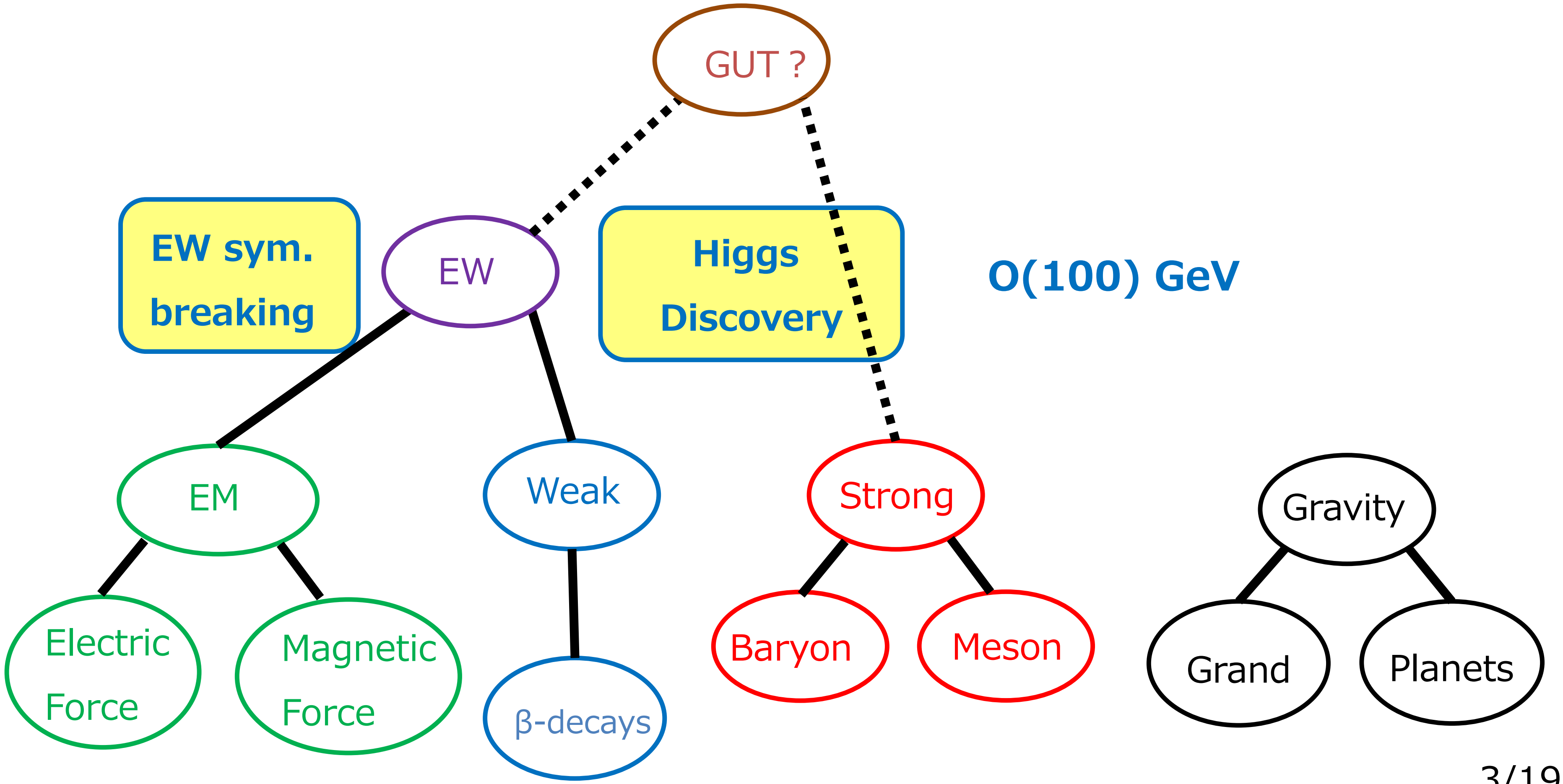

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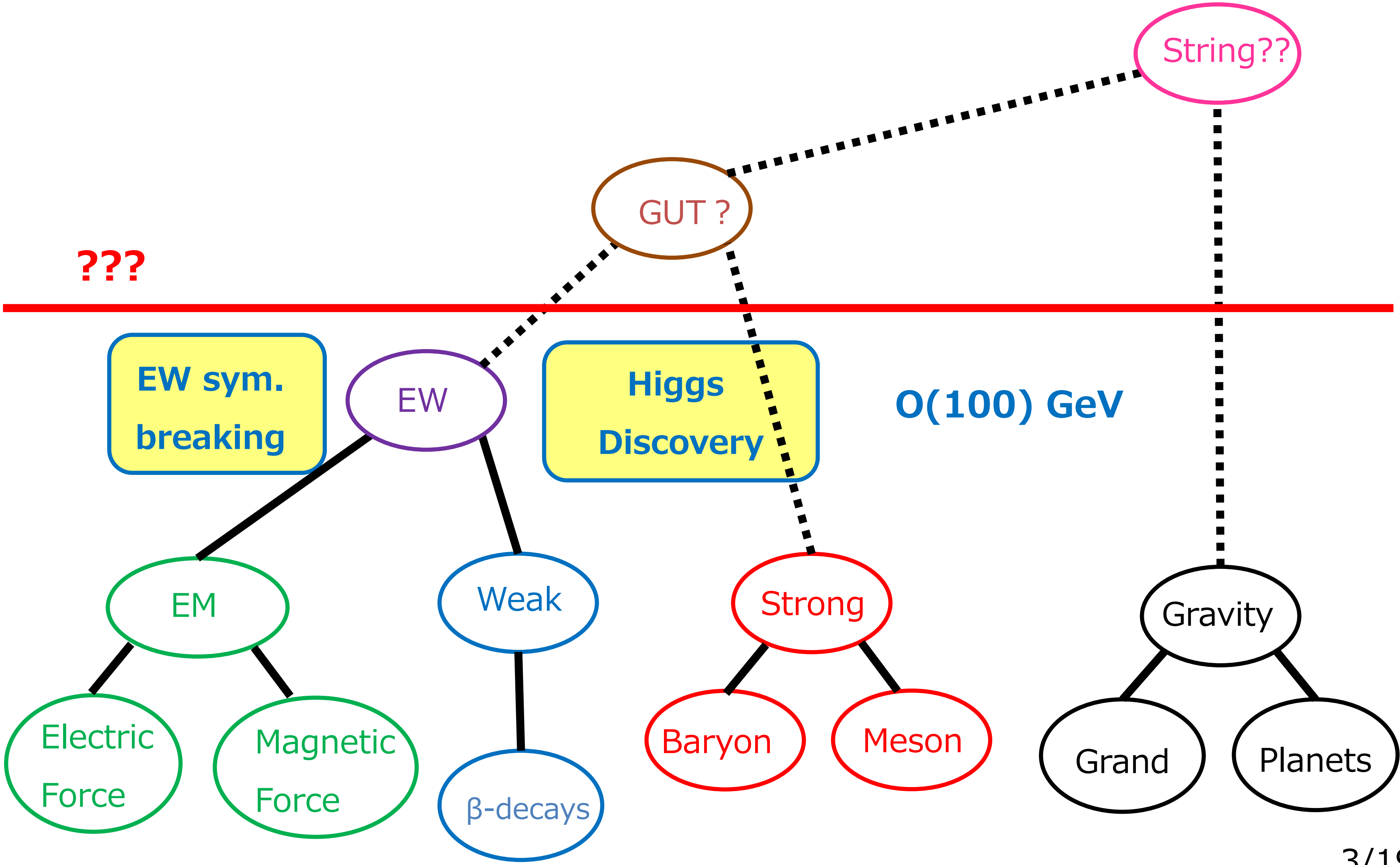


What is the BSM?

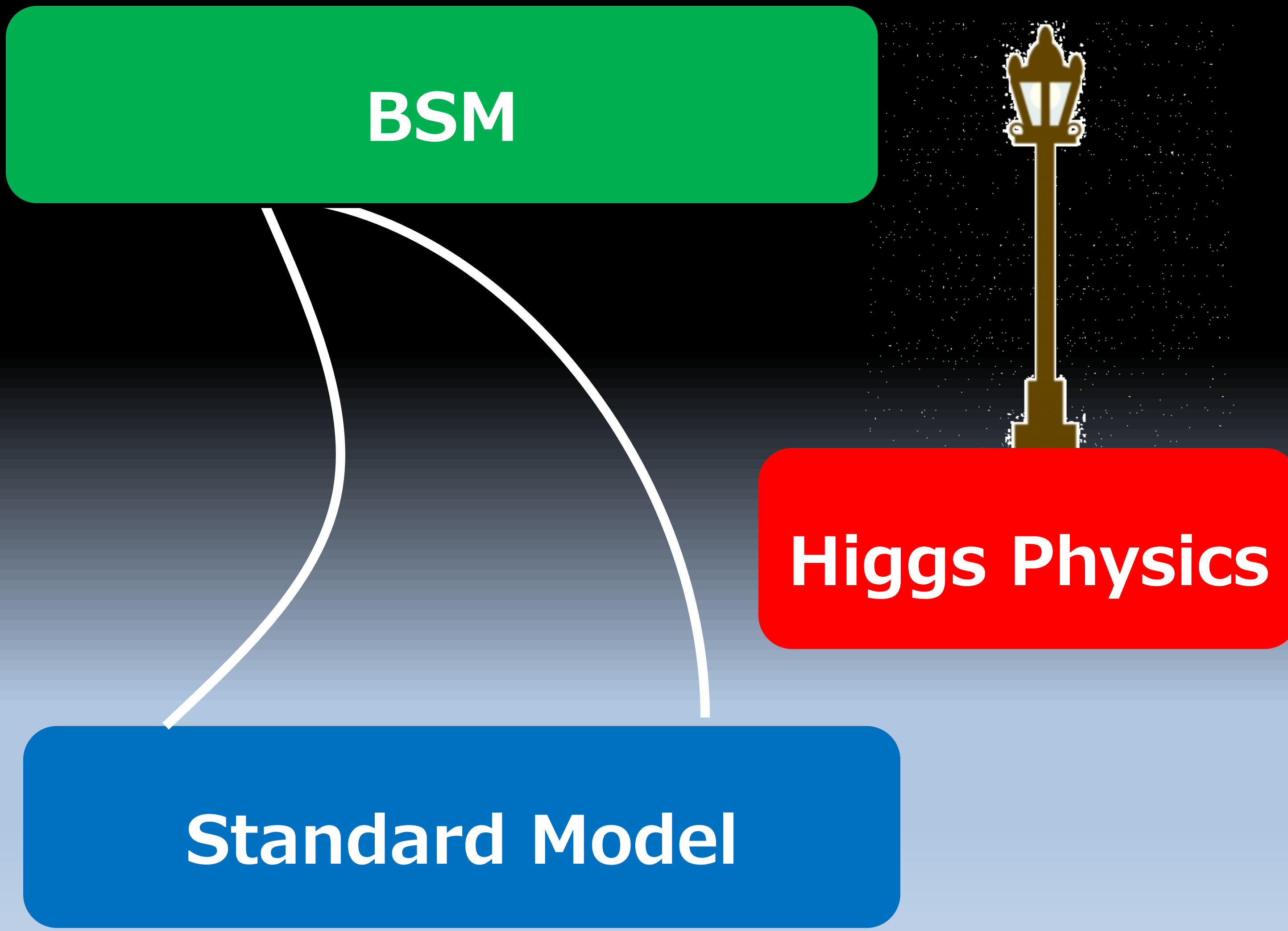
Which scale does the BSM appear?

Higgs Physics "lights" the way to BSM

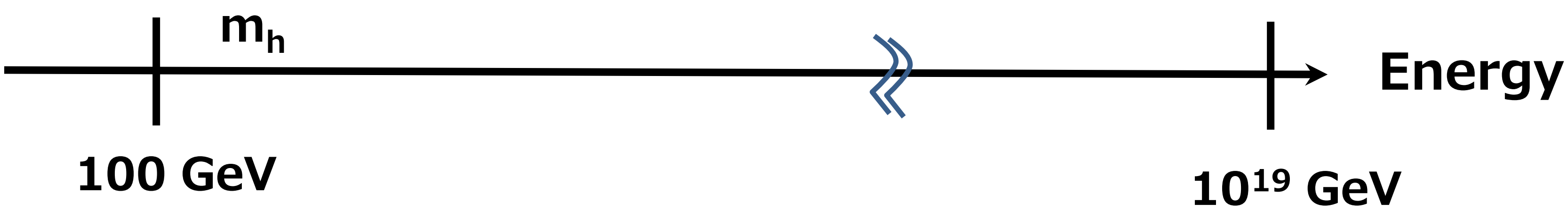
BSM

Standard Model

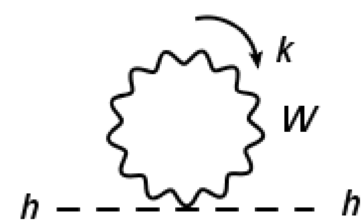
Higgs Physics “lights” the way to BSM



Nature of the Higgs → BSM



$$(125\ \mathrm{GeV})^2 \sim (m_h^0)^2 + \cancel{\frac{\Lambda^2}{16\pi^2} - \delta m_h^2}$$



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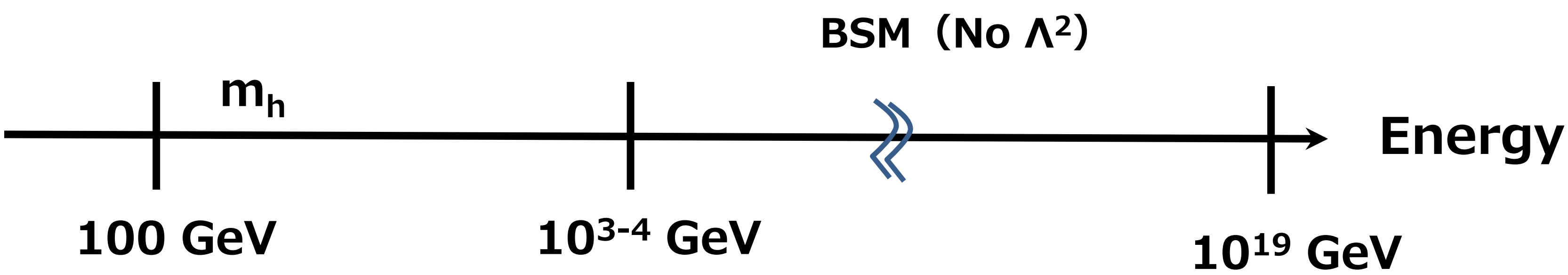

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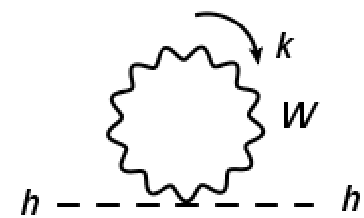
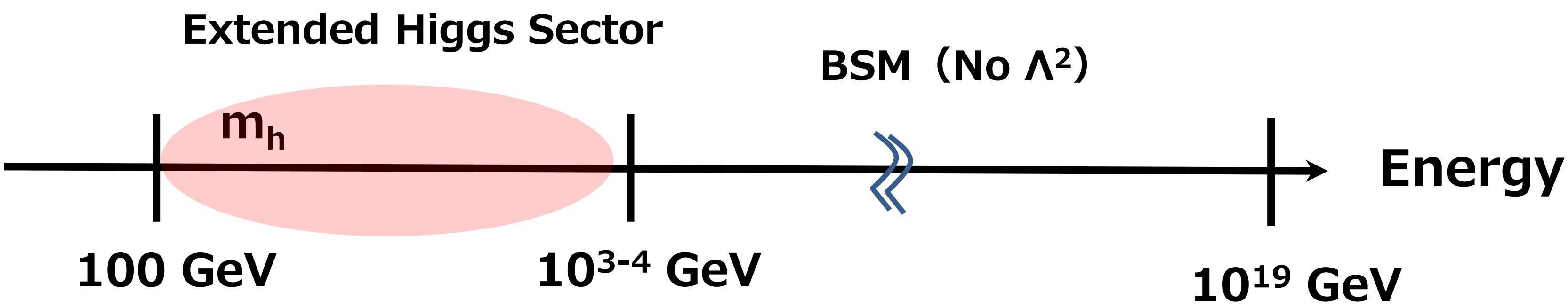


Higgs is
- Scalar boson (Supersymmetry) : Chiral Symmetry
- Fermion (Compositeness) : Chiral Symmetry
- Gauge boson (Gauge-Higgs Unification): Gauge Symmetry

Nature of the Higgs → BSM



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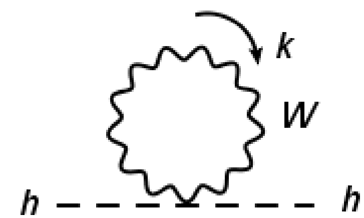

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Plan of Talk

I. Introduction

II. Higgs is a key to open the BSM (Bottom-up)

- Precise calculation of the Higgs properties

III. Higgs is a key to open the BSM (Top-down)

- SUSY VS Compositeness

IV. Summary

Higgs Precision Physics is Important

HL-LHC, ILC, ⋯

Loop level calc.

Precise measurements/calculations of h(125) properties

(couplings, width, BRs, cross sections, ⋯)

When deviations are found

We can extract

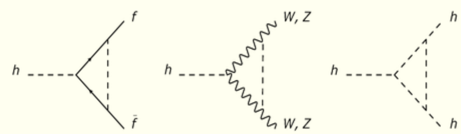
2^{nd} Higgs scale and Higgs structure!!

”No-Loose Theorem” of the Higgs Physics

H-COUP

Kanemura, Kikuchi, Sakurai, KY, Comp. Phys. Comm. 233, 134-144 (2018)

H-COUP



H-COUP is a calculation tool composed of a set of Fortran codes to compute the renormalized Higgs boson couplings with radiative corrections in various non-minimal Higgs models, such as the Higgs singlet model, four types of two Higgs doublet models and the inert doublet model. The impolved on-shell renormalization scheme is adopted, where the gauge depdence is eliminated.

Authors: Shinya Kanemura, Mariko Kikuchi, Kodai Sakurai and Kei Yagyu

The manual for H-COUP version 1.0 can be taken on arXiv:1710.04603 [hep-ph].

Downloads

- H-COUP version 1.0 : [HCOUP-1.0.zip] [The manual is here]

□ Models

SM | Higgs Singlet Model | 2HDMs (4 types and inert model)

Φ

Φ S

Φ Φ′

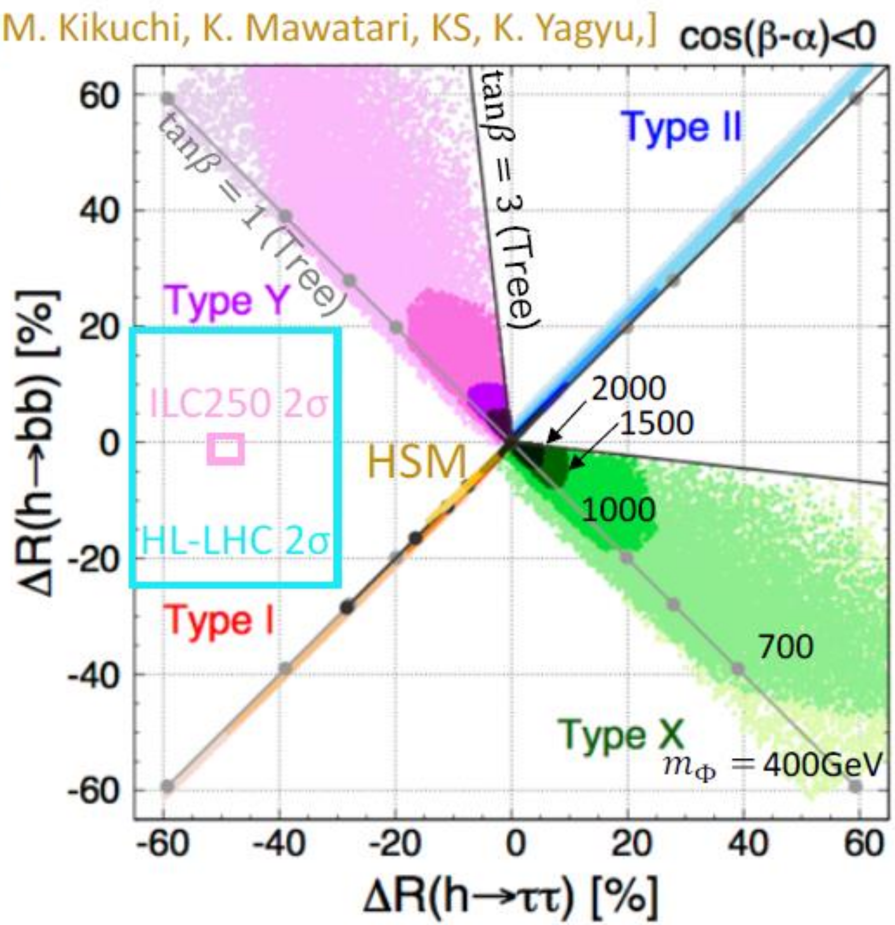
Kanemura, Kikuchi, KY, NPB907 (2016)
Kanemura, Kikuchi, KY, NPB917 (2017)

Kanemura, Kikuchi, KY, PLB731 (2014)
Kanemura, Kikuchi, KY, NPB896 (2015)
Kanemura, Kikuchi , Sakurai, PRD

$\Delta R(h \to b\bar{b})$ vs $\Delta R(h \to \tau\bar{\tau})$

$$\Delta R(\mathrm{h} \to XX) = \frac{\Gamma(\mathrm{h} \to XX)_{EX}}{\Gamma(\mathrm{h} \to XX)_{SM}} - 1$$

- Color plots : predictions at the 1-loop level for each model
- A contrast of color : values of mass of extra Higgs bosons
- Black line : predictions at the tree level ($tan\beta = 1{,}3$).



→ by the directions of deviations, 4 types of THDMs are discriminated.

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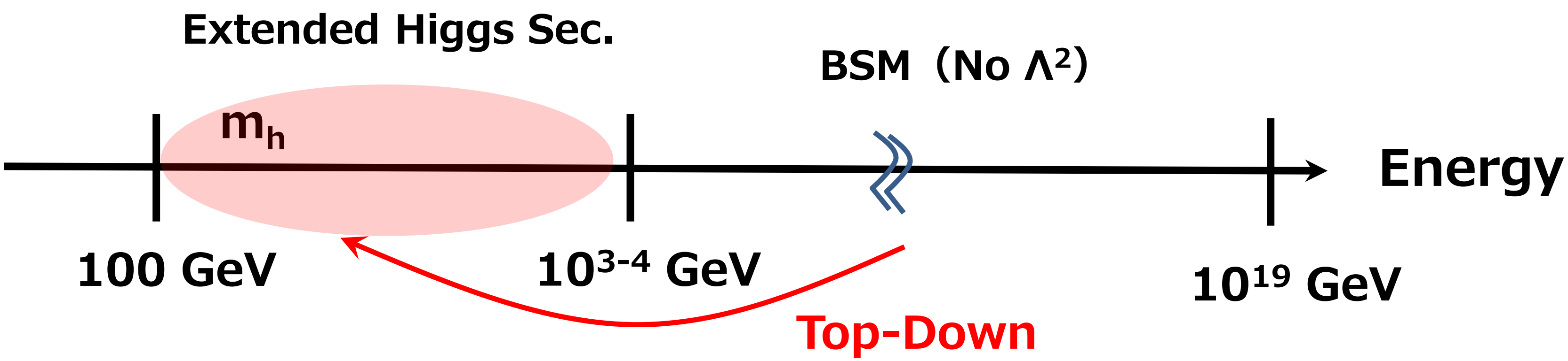
Nature of the Higgs → BSM



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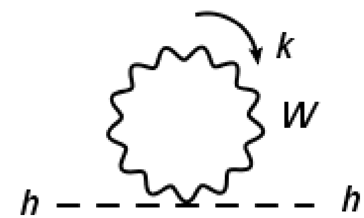

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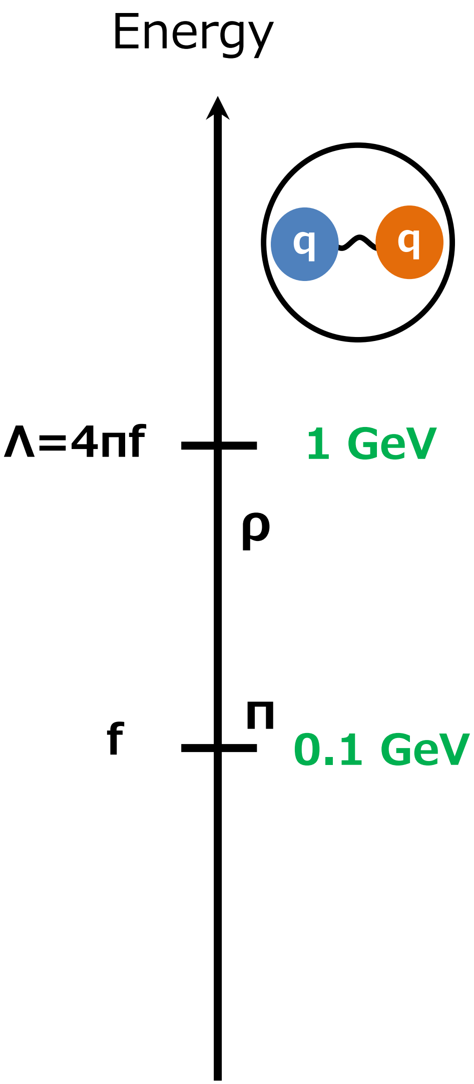
Pion and Composite Higgs

Georgi, Kaplan (1984)



QCD (no scalar)

$$G = SU(2)_L \times SU(2)_R$$

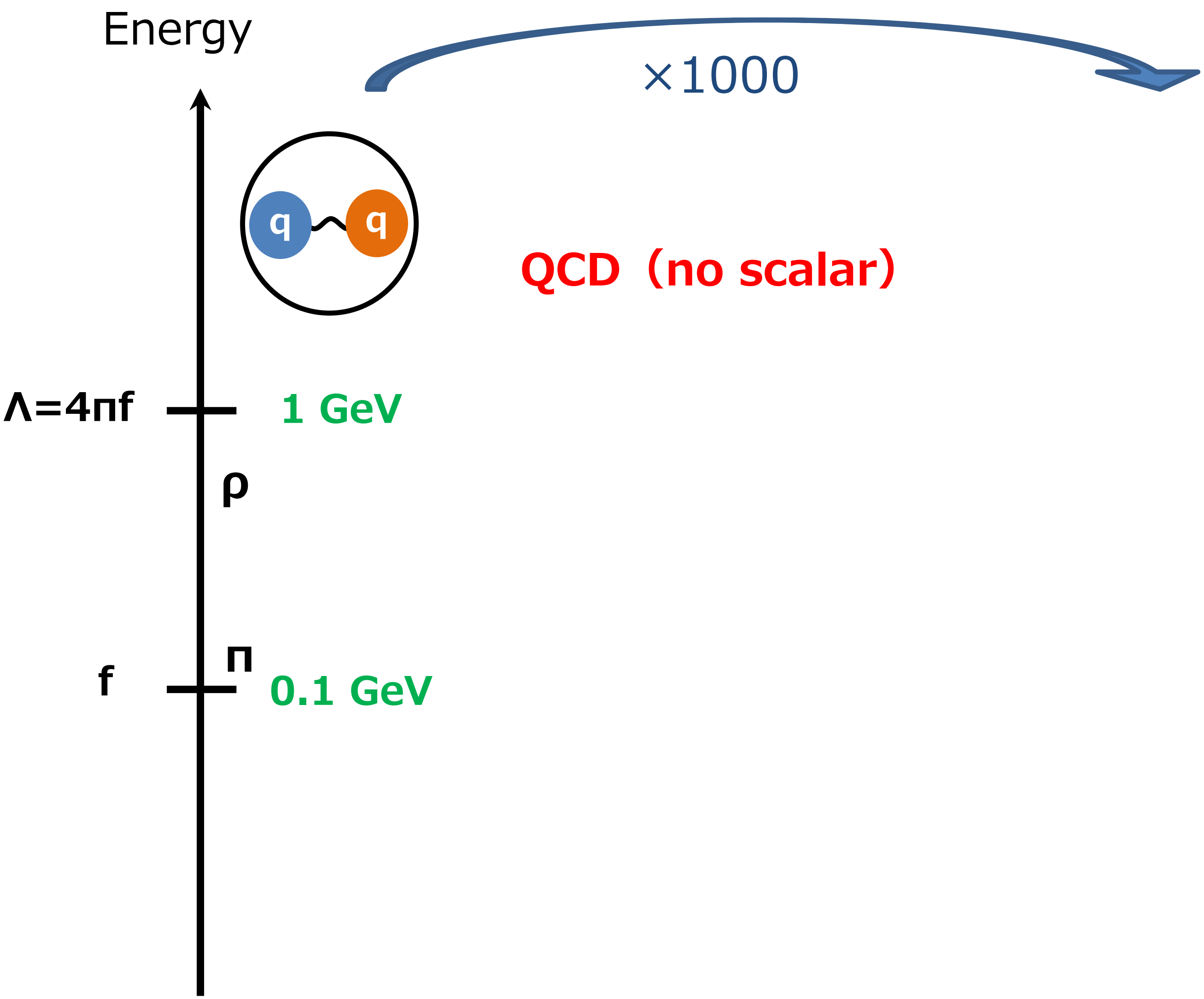
Non-pert. effects

$$H = SU(2)_V$$

Non-linear Σ model

Pion and Composite Higgs

Georgi, Kaplan (1984)



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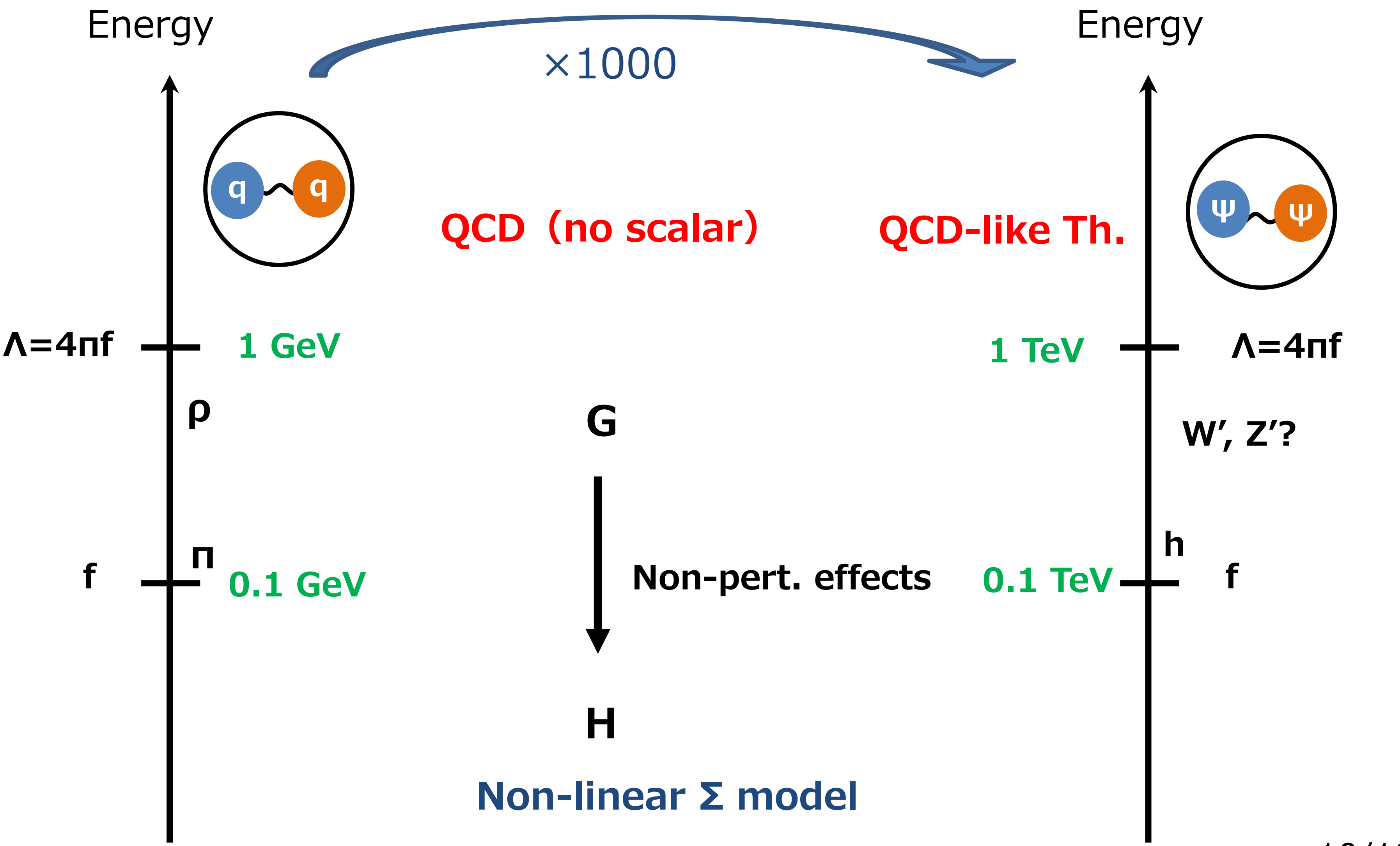

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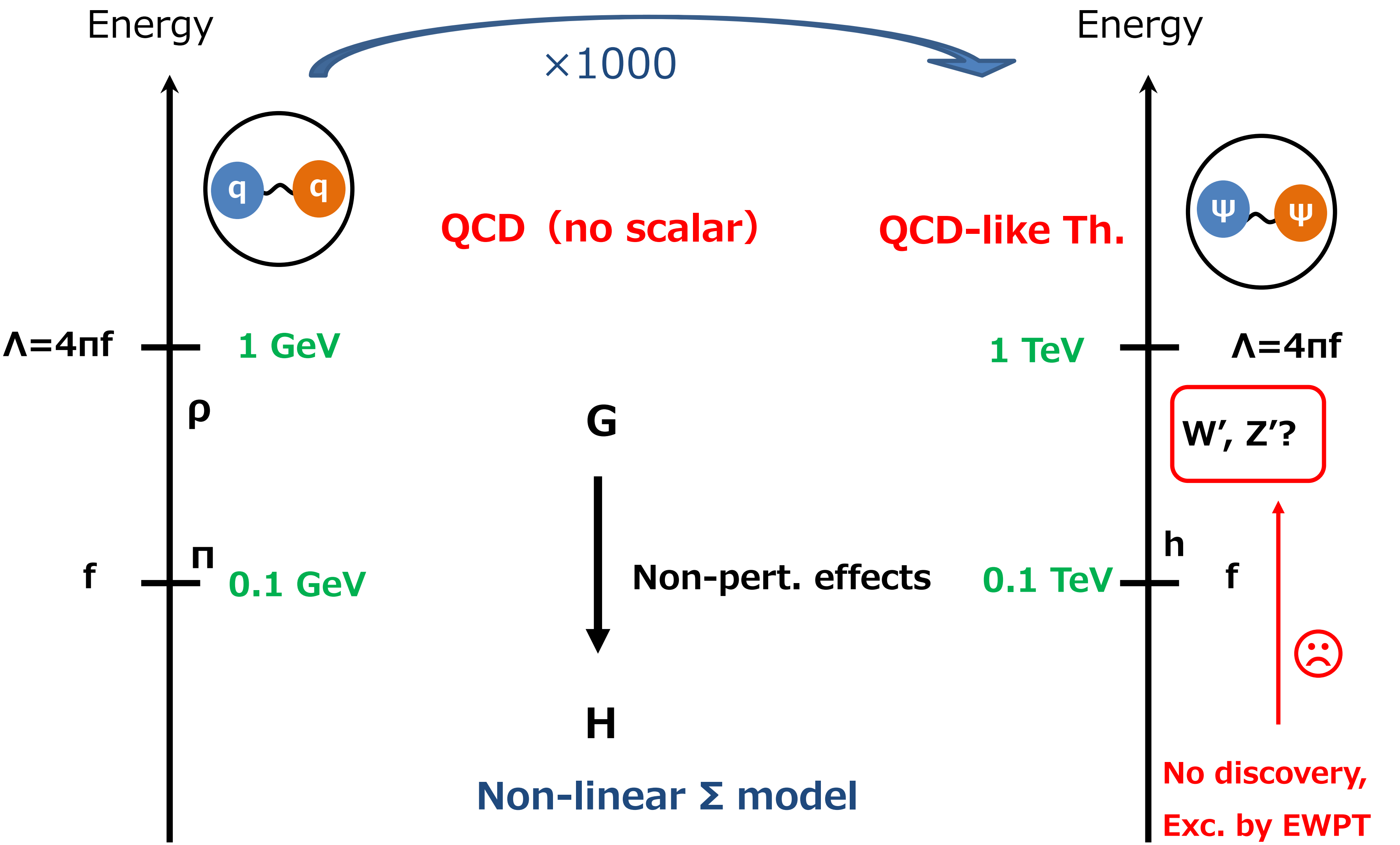

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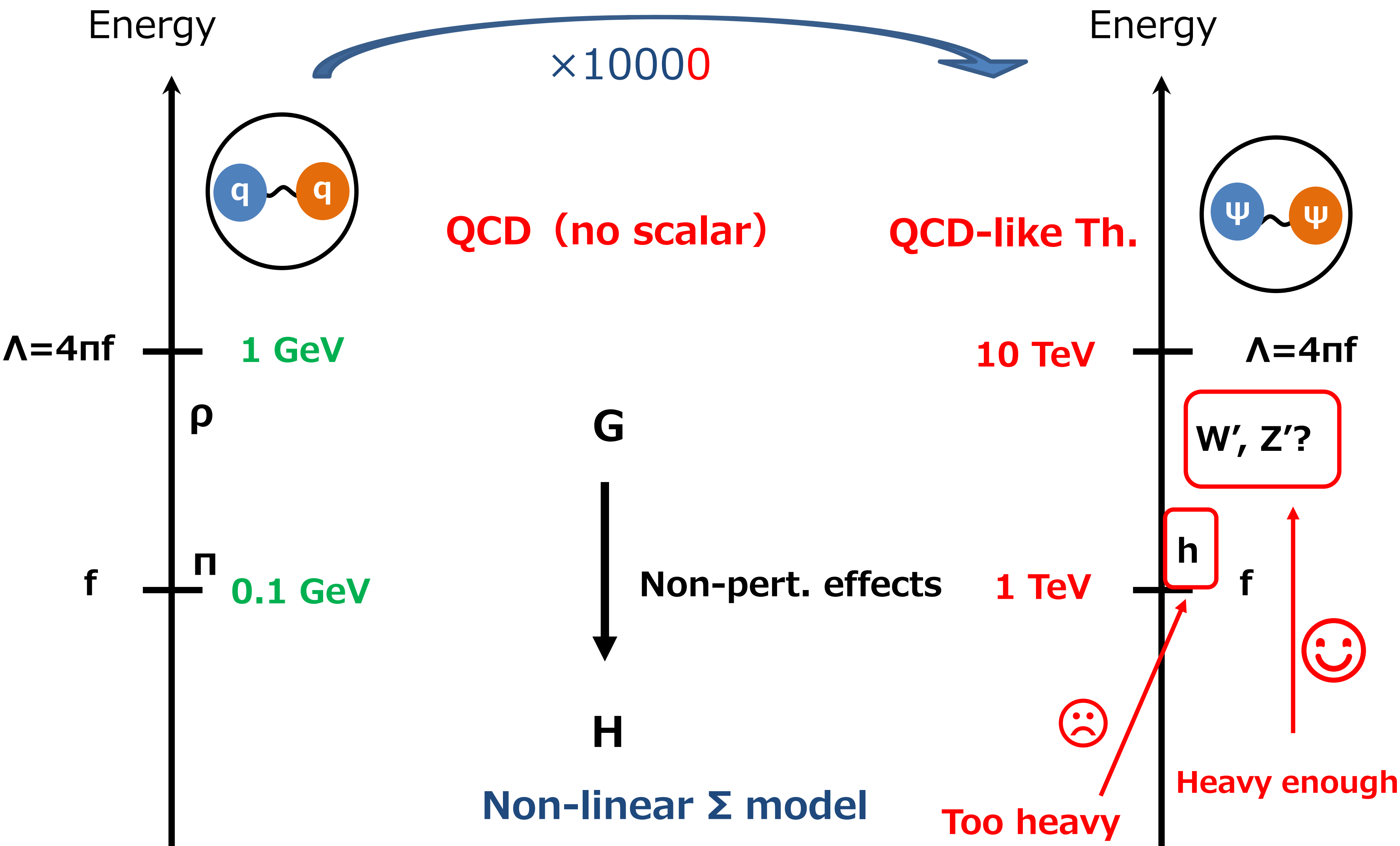

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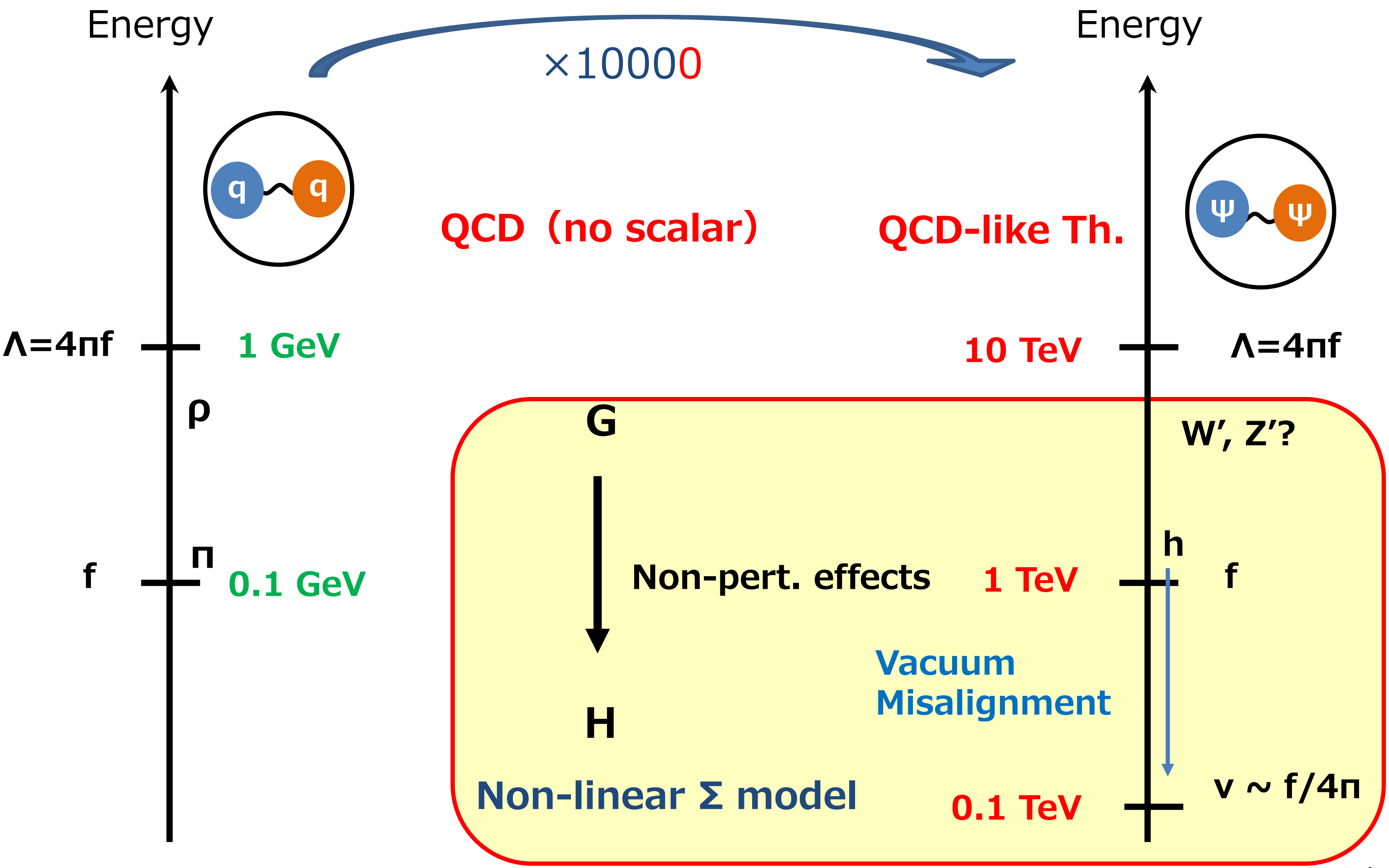


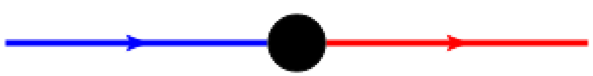
Higgs Potential

- Due to the shift symmetry of the NGB, the Higgs potential is 0 at any order of perturbation. → Higgs boson is massless.

- We need to introduce an explicit breaking of G.
  → Higgs becomes pseudo-NGB with a finite mass.

Kaplan, PLB365, 259 (1991)

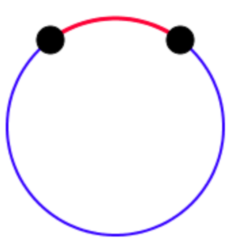
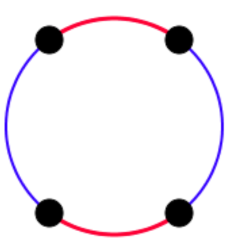
- Explicit breaking can be introduced via partial compositeness mechanism.



Linear mixing

Elementary sector (SM particles)

Strong sector particles

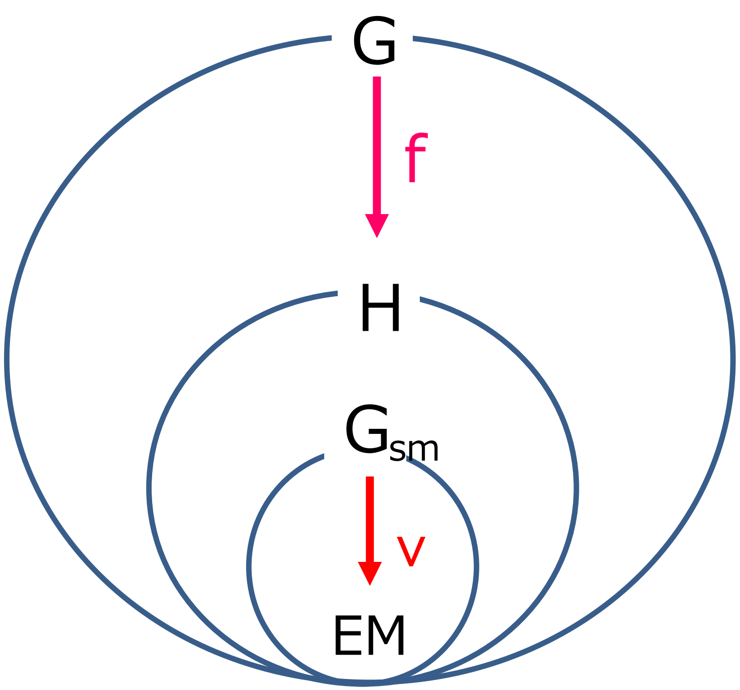
Potential =  +  + …

Vacuum misalignment
can be realized!!

Basic Rules for the Construction

- The structure of the Higgs sector is determined by the coset G/H.
- H should contain the custodial $SO(4) \simeq SU(2)_L \times SU(2)_R$ symmetry.
- The number of NGBs (dimG-dimH) must be 4 or lager.
- Explicit breaking of G must be introduced.

Mrazek et al, NPB 853 (2011) 1-48



G [dim]	H [dim]	Higgs sector
SO(5) [10]	SO(4) [6]	Φ *Agashe, Contino, Pomarol (2005)*
SO(6) [15]	SO(5) [10]	Φ + S
SO(6) [15]	SO(4)×SO(2) [7]	
SU(5) [24]	SU(4)×U(1) [16]	Φ + Φ′
Sp(6) [21]	Sp(4)×SU(2) [13]	
SU(5) [24]	SO(5) [10]	Φ + Δ + S
		etc

SUSY ?

ex. MSSM

or

Composite (pNGB) ?

ex. SO(6) $\rightarrow$ SO(4) $\times$ SO(2)

Q. When the 2HDM is realized as EFT…

Properties of the 2HDM tell us the direction!

Composite 2HDM (C2HDM)

De Curtis, Delle Rose, Moretti, KY, arXiv: 1803.01865 [hep-ph] (PLB)

- G→H: SO(6) → SO(4)×SO(2)

- SO(6) generators (15): $T^A = \{\underbrace{T^a_{L,R}}_{\text{6 SO(4)}},\ \underbrace{T_S}_{\text{1 SO(2)}},\ \underbrace{T^{\hat{a}}_{1,2}}_{\text{8 Broken}}\}$ (A=1-15, a=1-3, $\hat{a}$=1-4)

- NGB Mat.: $$U = \exp\sqrt{2}i\left[T_1^{\hat{a}}\frac{\phi_1^{\hat{a}}}{f} + T_2^{\hat{a}}\frac{\phi_2^{\hat{a}}}{f}\right] = \exp\frac{-i}{f}\begin{pmatrix} 0 & 0 & 0 & 0 & \phi_1^1 & \phi_2^1 \\ 0 & 0 & 0 & 0 & \phi_1^2 & \phi_2^2 \\ 0 & 0 & 0 & 0 & \phi_1^3 & \phi_2^3 \\ 0 & 0 & 0 & 0 & \phi_1^4 & \phi_2^4 \\ -\phi_1^1 & -\phi_1^2 & -\phi_1^3 & -\phi_1^4 & 0 & 0 \\ -\phi_2^1 & -\phi_2^2 & -\phi_2^3 & -\phi_2^4 & 0 & 0 \end{pmatrix}$$

2 Higgs Doublets

- **15**-plet : $$\Sigma = U\Sigma_0 U^T$$

$$\Sigma_0 = i\sqrt{2}T_S = \begin{pmatrix} 0_{4\times4} & 0_{4\times2} \\ 0_{2\times4} & i\sigma_2 \end{pmatrix}$$

$$\Sigma \underset{g}{\rightarrow} \Sigma' = g\,\Sigma\,g^{-1}$$

Structure of the C2HDM

$$\mathcal{L} = \mathcal{L}_{\mathbf{elem}} + \mathcal{L}_{\mathbf{str}} + \mathcal{L}_{\mathbf{mix}}$$

Structure of the C2HDM

$$\mathcal{L} = \mathcal{L}_{\rm elem} + \mathcal{L}_{\rm str} + \mathcal{L}_{\rm mix}$$

Elementary Sector

$SO(6)\times U(1)_X$

A_μ^A, q_L^r, t_R^r

15-plet **6-plet**

$SU(2)_L\times U(1)_Y$

W_μ^a, q_L, t_R

Mixing

Partial Compositeness

2 of $SU(2)_L$ | **2** of $SU(2)_R$

2 of $SO(2)$

q_L t_R

Strong Sector

$SO(6)\times U(1)_X \rightarrow$

$SO(4)\times SO(2)\times U(1)_X$

ρ_μ^A, Ψ^r, Σ

15-plet **6-plet** **15-plet**

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Mixing

Partial Compositeness

Integrate
ρ and ψ

Strong Sector

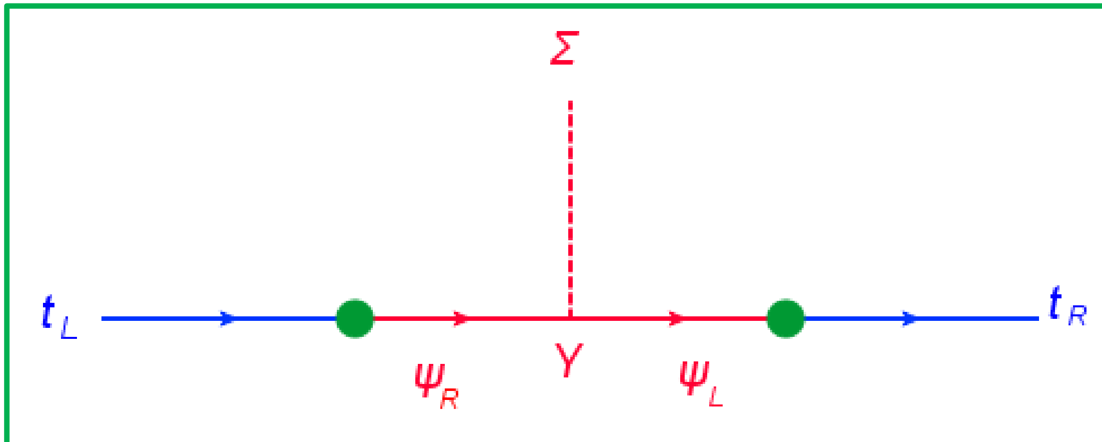
SO(6)×U(1)$_X$ →
SO(4)×SO(2)×U(1)$_X$

ρ^A_μ, Ψ^r, Σ

15-plet **6-plet** **15-plet**

SU(2)×U(1) inv. effective Lagrangian（SM fields + form factors with Σ)

Structure of the C2HDM



$\mathrm{tr} + \mathcal{L}_{\mathrm{mix}}$

Strong Sector

SO(6)×U(1)$_X$ →

Mixing

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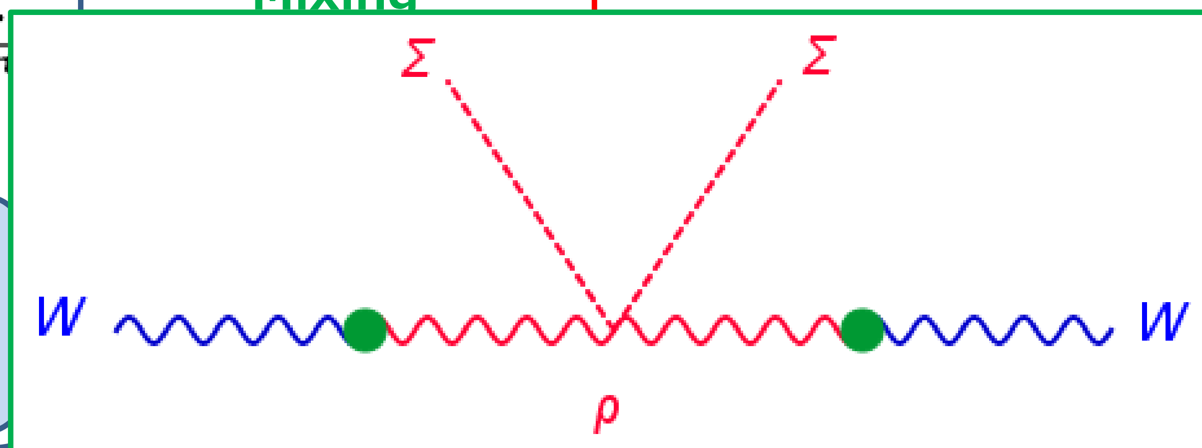

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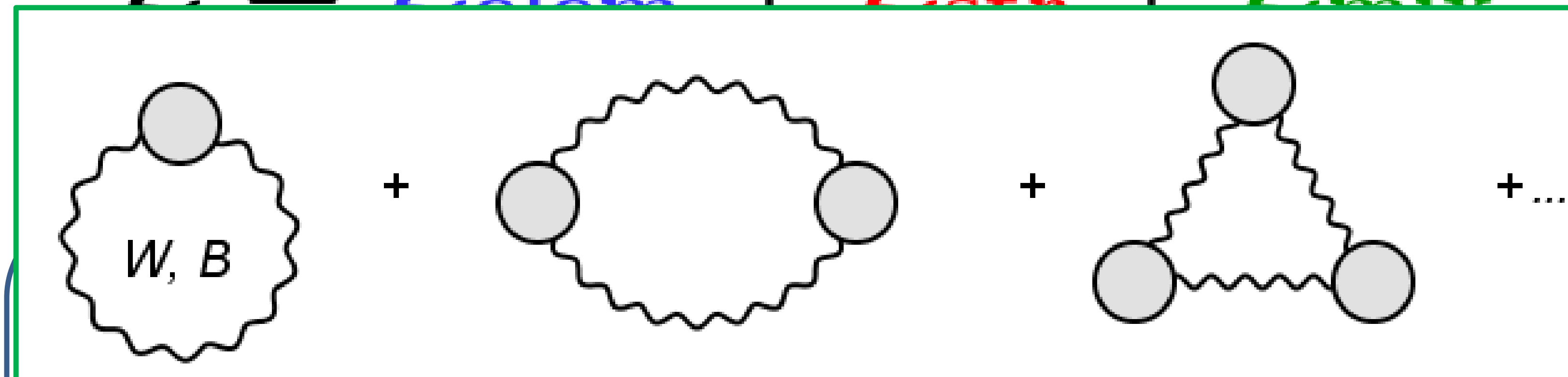
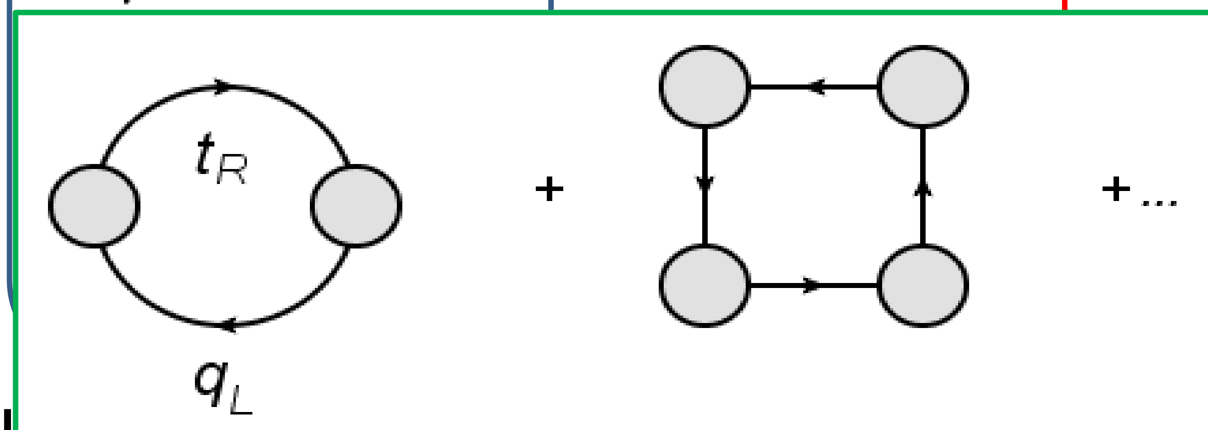
Higgs potential（Coleman-Weinberg mechanism）

Structure of the C2HDM

$$\mathcal{L} = \mathcal{L}_{elem} + \mathcal{L}_{str} + \mathcal{L}_{mix}$$





A_μ, Ψ^r, Σ

let 6-plet 15-plet

SU ... factors with Σ)

Higgs potential（Coleman-Weinberg mechanism）

Structure of the C2HDM

$$V(\Phi_1,\Phi_2) = m_1^2\Phi_1^\dagger\Phi_1 + m_2^2\Phi_2^\dagger\Phi_2 - \left[m_3^2\Phi_1^\dagger\Phi_2 + \mathrm{h.c.}\right]$$
$$+\frac{\lambda_1}{2}(\Phi_1^\dagger\Phi_1)^2 + \frac{\lambda_2}{2}(\Phi_2^\dagger\Phi_2)^2 + \lambda_3(\Phi_1^\dagger\Phi_1)(\Phi_2^\dagger\Phi_2) + \lambda_4(\Phi_1^\dagger\Phi_2)(\Phi_2^\dagger\Phi_1)$$
$$+\frac{\lambda_5}{2}(\Phi_1^\dagger\Phi_2)^2 + \lambda_6(\Phi_1^\dagger\Phi_1)(\Phi_1^\dagger\Phi_2) + \lambda_7(\Phi_2^\dagger\Phi_2)(\Phi_1^\dagger\Phi_2) + \mathrm{h.c.}$$

$SU(2)_L \times U(1)_Y$

W_μ^a, q_L, t_R

Integrate
ρ and ψ

ρ_μ^A, Ψ, Σ

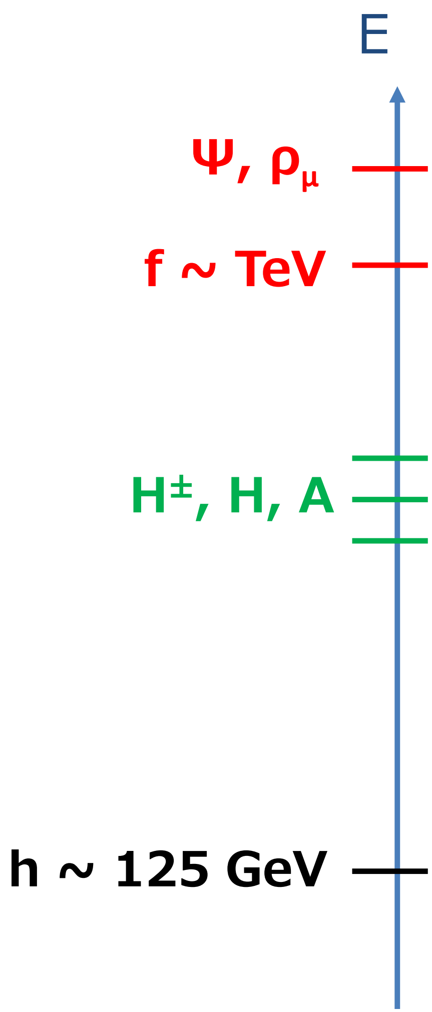
15-plet **6-plet** **15-plet**

+ $O(\Phi^6)$

SU(2)×U(1) inv. effective Lagrangian（SM fields + form factors with Σ)

Higgs potential（Coleman-Weinberg mechanism)

Typical Prediction of Mass Spectrum



★f → ∞ : All extra Higgses are decoupled

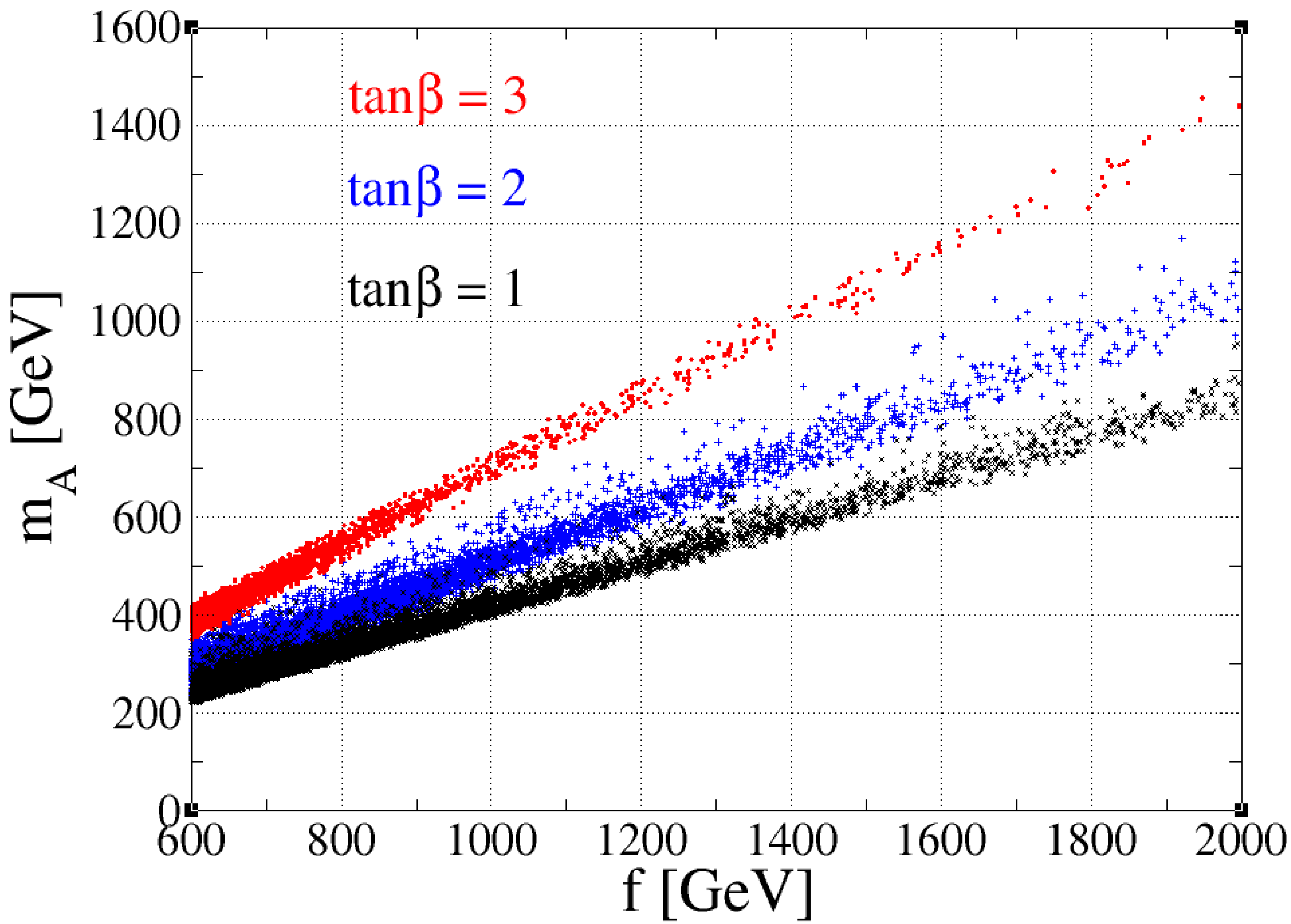
→ (elementary) SM limit

$$M^2 \sim \frac{f^2}{16\pi^2}$$

$$m_h^2 \sim N_c \frac{g_\rho^2 m_t^2}{16\pi^2}$$

Correlation b/w f and m_A

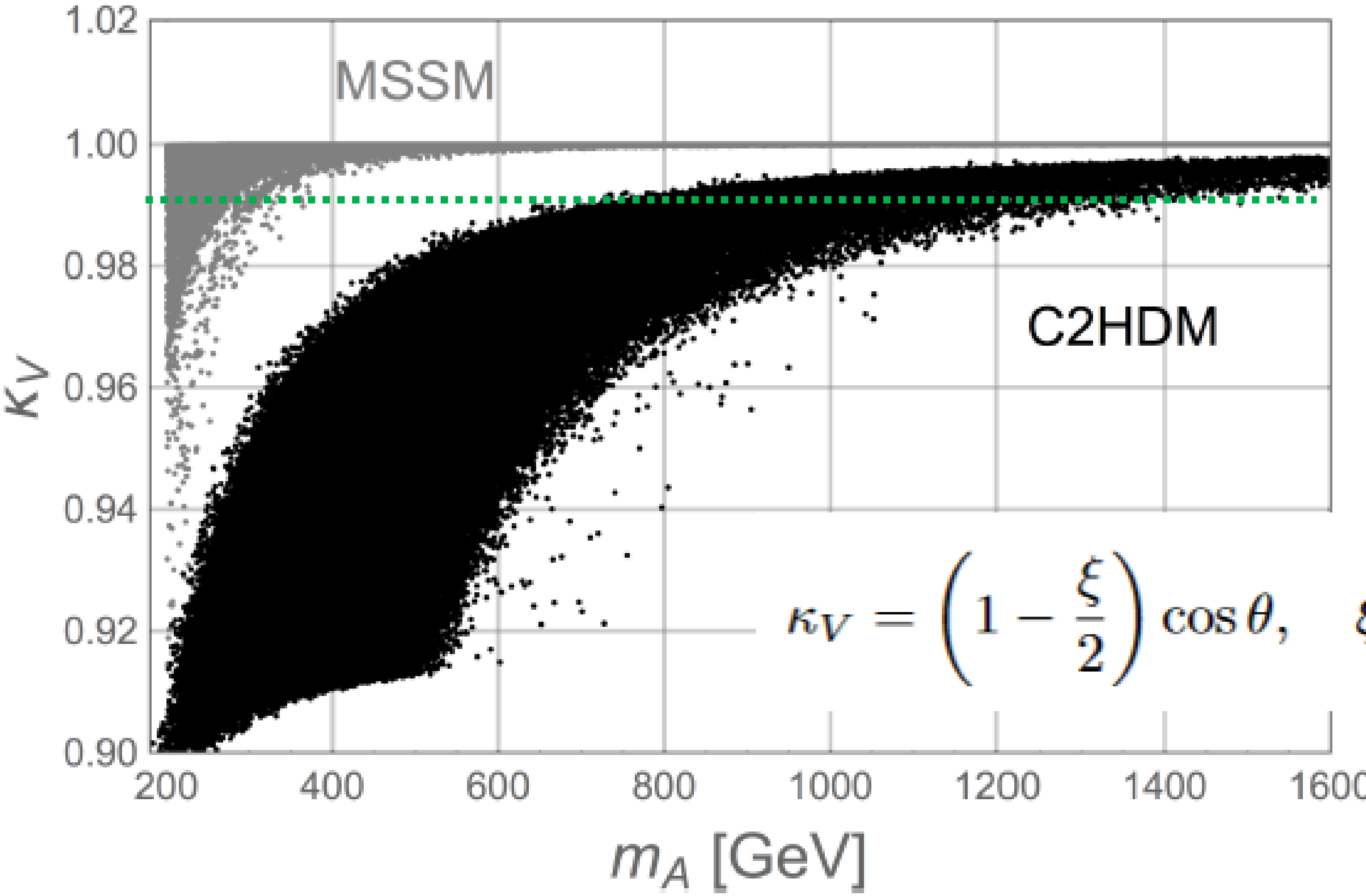
De Curtis, Delle Rose, Moretti, KY, arXiv: 1803.01865 [hep-ph]



Correlation b/w m_A and κ_V ($= g_{hVV}/g_{hVV}^{SM}$)

De Curtis, Delle Rose, Moretti, KY, arXiv: 1803.01865 [hep-ph]

MSSM: FeynHiggs v2.14.1



$$\kappa_V = \left(1 - \frac{\xi}{2}\right)\cos\theta, \quad \xi \equiv \frac{v_{\rm SM}^2}{f^2}$$

Summary

- Higgs Physics is a “light” to show the scale and direction of the BSM.

  \- Particular structure of the Higgs sector appears from the BSM as the LE EFT.

- Bottom-up: precise calculations of the Higgs property (coupling, BRs, ···) in various non-minimal Higgs sectors will tell us the **scale of the 2^{nd} Higgs boson** and the

Thanks for attention!

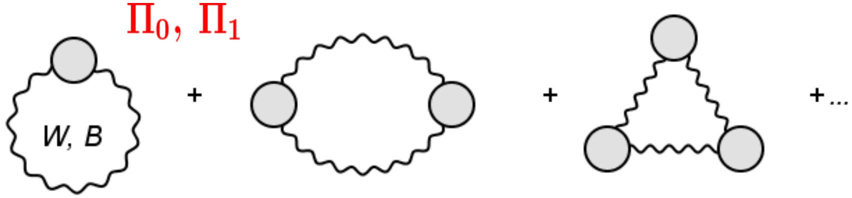
ss can be distinguished from the 2HDM properties,

the C2HDM is much slower than the MSSM.

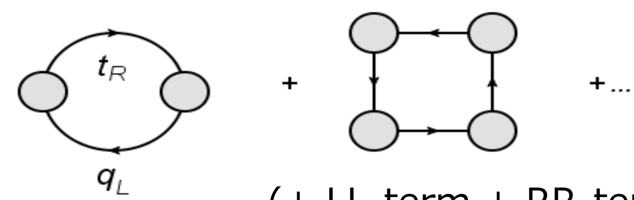
Effective Potential

- The Higgs potential can be calculated as

Π_0, Π_1



M_1



(+ LL-term + RR-term)

$$\boxed{V = \frac{9}{2}\int \frac{d^4k}{(2\pi)^4} \underline{\ln\det D_V^{-1}} - 2N_c \int \frac{d^4k}{(2\pi)^4} \underline{\ln\det D_F^{-1}}}$$

$$\boxed{\sim \frac{\Pi_1}{4\Pi_0}\sin^2\frac{\phi}{f}} \qquad \boxed{\sim \frac{M_1^2}{k^2}\sin^2\frac{\phi}{f}\cos^2\frac{\phi}{f}}$$

$$\sim \alpha \sin^2\frac{\phi}{f} - \beta \sin^2\frac{\phi}{f}\cos^2\frac{\phi}{f} \qquad \frac{v}{f} = \sin\frac{\langle\phi\rangle}{f} = \sqrt{\frac{\beta-\alpha}{2\beta}}$$

$$m_h^2 = \frac{2}{f^2}\frac{\beta^2-\alpha^2}{\beta} \sim 8v^2\frac{\beta}{f^4} = 8v^2\frac{b}{16\pi^2} \quad \sim (125\ \mathrm{GeV})^2 \times (0.2b)$$

Little Higgs & (Holographic) CH

Review: Brando, Csaba, Javi, arXiv: 1401.2457 [hep-ph]

$$V(h) = \frac{g_{\rm SM}^2 \Lambda^2}{16\pi^2}\left(-ah^2 + b\frac{h^4}{2f^2}\right) = g_{\rm SM}^2 f^2 \left(-ah^2 + b\frac{h^4}{2f^2}\right)$$

f: Composite scale ~TeV

(Λ = 4πf: NDA)

$$\Rightarrow \quad (246\ \mathrm{GeV})^2 = v^2 = \frac{a}{b} f^2 \qquad (125\ \mathrm{GeV})^2 = m_h^2 = 4b g_{\rm SM}^2 v^2$$

Little Higgs Models : a ~ $(1/16\pi^2)$, b ~ O(1)

$v \sim f/4\pi$, $m_h \sim 2vg_{sm}$

Natural VEV,

but tuning is needed for m_h

(Holographic) Composite Higgs Models : a, b ~ $O(1/16\pi^2)$

$v \sim f$, $m_h \sim vg_{sm}/2\pi$

Natural m_h,

but tuning is needed for v

Explicit Model

Based on the 4DCHM, De Curtis, Redi, Tesi, JHEP04 (2012) 042

$$\mathcal{L}_{\mathrm{elem}} = -\frac{1}{4} W^a_{\mu\nu} W^{a\mu\nu} + \bar{q}_L \, i\not{D} \, q_L + \bar{t}_R \, i\not{D} \, t_R$$

Elementary Sector

$SU(2)_L \times U(1)_Y$

$\boldsymbol{W^a_\mu, \; q_L, \; t_R}$

Mixing

Partial Compositeness

Strong Sector

$SO(6) \times U(1)_X$

$\rightarrow SO(4) \times SO(2) \times U(1)_X$

$\boldsymbol{\rho^A_\mu, \; \Psi^6, \; \Sigma}$

Explicit Model

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$$\mathcal{L}_{\rm elem} = -\frac{1}{4}W^a_{\mu\nu}W^{a\mu\nu} + \bar{q}_L\, i\not{D}\; q_L + \bar{t}_R\, i\not{D}\; t_R$$

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Mixing

Partial Compositeness

Strong Sector

SO(6)×U(1)$_X$

→ SO(4)× SO(2)×U(1)$_X$

$\rho^A_\mu,\ \Psi^6,\ \Sigma$

$$\mathcal{L}_{\rm str} = \bar{\Psi}^6(i\not{D} - m_\Psi)\Psi^6 - \bar{\Psi}^6_L(Y_1\Sigma + Y_2\Sigma^2)\Psi^6_R + \text{h.c.}$$

$$-\frac{1}{4}\,{\rm tr}\rho^A_{\mu\nu}\rho^{A\,\mu\nu} + \frac{m_\rho^2}{2}(\rho^A)_\mu(\rho^A)^\mu$$ + (Σ-ρ) interactions

Explicit Model

Based on the 4DCHM, De Curtis, Redi, Tesi, JHEP04 (2012) 042

C_2 symmetry

(to avoid FCNCs)

$$U(\phi_1^{\hat{a}}, \phi_2^{\hat{a}}) \to C_2 U(\phi_1^{\hat{a}}, \phi_2^{\hat{a}}) C_2 = U(\phi_1^{\hat{a}}, -\phi_2^{\hat{a}})$$

$$\Sigma \to -C_2 \Sigma C_2$$

$$\Psi^6 \to C_2 \Psi^6$$

C_2 = diag(1,1,1,1,1,-1)

Elementary Sector

$SU(2)_L \times U(1)_Y$

$$W_\mu^a, \; q_L, \; t_R$$

Mixing

Partial Compositeness

Strong Sector

$SO(6) \times U(1)_X$

$\to SO(4) \times SO(2) \times U(1)_X$

$$\rho_\mu^A, \; \Psi^6, \; \Sigma$$

$$\mathcal{L}_{\rm str} = \bar{\Psi}^6 (i\not{D} - m_\Psi)\Psi^6 - \bar{\Psi}_L^6 (\cancel{Y_1 \Sigma} + Y_2 \Sigma^2)\Psi_R^6 + \text{h.c.}$$

$$-\frac{1}{4}\,\text{tr}\rho_{\mu\nu}^A \rho^{A\,\mu\nu} + \frac{m_\rho^2}{2}(\rho^A)_\mu (\rho^A)^\mu$$ + (Σ-ρ) interactions

Explicit Model

Based on the 4DCHM, De Curtis, Redi, Tesi, JHEP04 (2012) 042

Embeddings into SO(6) multiplets :

$$W_\mu^a \in W_\mu^A \qquad q_L \in q_L^6 \qquad t_R \in t_R^6$$

Elementary Sector

SU(2)$_L$×U(1)$_Y$

$$W_\mu^a, \; q_L, \; t_R$$

Mixing

Partial Compositeness

Strong Sector

SO(6)×U(1)$_X$

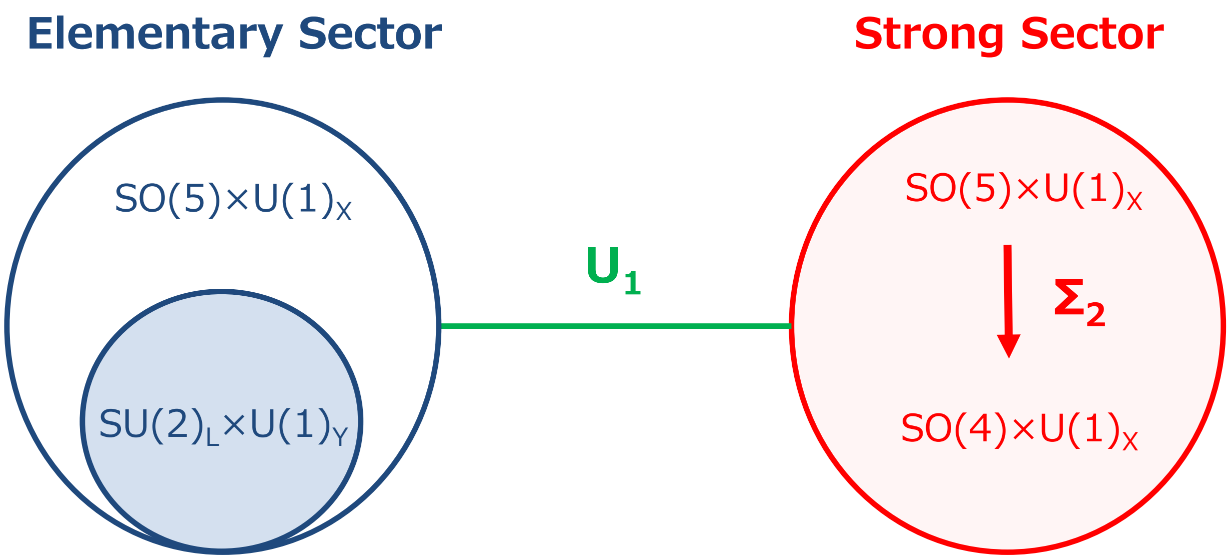
→ SO(4)× SO(2)×U(1)$_X$

$$\rho_\mu^A, \; \Psi^6, \; \Sigma$$

$$\mathcal{L}_{\rm mix} = (f^2 g_\rho g_W) W_\mu^A \rho^{A\mu} + (\Delta_L \bar{q}_L^6 \Psi_R^6 + \Delta_R \bar{t}_R^6 \Psi_L^6 + \text{h.c.})$$

2-site model: Gauge sector

De Curtis, Redi, Tesi, JHEP04 (2012) 042



$$U_1 \to g_L U_1 g_R^\dagger$$

~1

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

$$\Sigma_2 \to g \Sigma_2$$

~Σ_0

$SO(5) \to SO(4)$

$$\mathcal{L}_{2\text{-site}} = \boxed{-\frac{1}{4g_A^2} A^A_{\mu\nu} A^{A\,\mu\nu}} + \boxed{\frac{f_1^2}{4}\mathrm{tr}|D_\mu U_1|^2} - \boxed{\frac{1}{4g_\rho^2}\rho^A_{\mu\nu}\rho^{A\,\mu\nu} + \frac{f_2^2}{2}|D_\mu \Sigma_2|^2}$$

$$D_\mu U_1 = \partial_\mu U_1 - iA^A_\mu T^A U_1 + iU_1 \rho^A_\mu T^A \xrightarrow[U_1\sim 1]{} -i(A^A_\mu - \rho^A_\mu)T^A \quad \Rightarrow \quad m_\rho^2 = \frac{g_\rho^2}{2} f_1^2$$

$$D_\mu \Sigma_2 = (\partial_\mu - i\rho^A_\mu T^A)\Sigma_2 \xrightarrow[\Sigma_2\sim\Sigma_0]{} -i\rho^{\hat{a}}_\mu \quad \Rightarrow \quad m_{\hat{\rho}}^2 = \frac{g_\rho^2}{2}(f_1^2 + f_2^2)$$

Fermion Sector: 5-plet (MCHM$_5$)

De Curtis, Redi, Tesi, JHEP04 (2012) 042

- SO(5)×U(1)$_X$ invariant Lagrangian:

$$\mathcal{L}_{\text{2-site}} = \boxed{\frac{1}{y_L^2}\bar{q}_L^5 i\not{D}\, q_L^5 + \frac{1}{y_R^2}\bar{t}_R^5 i\not{D}\, t_R^5}$$

Elementary Sector

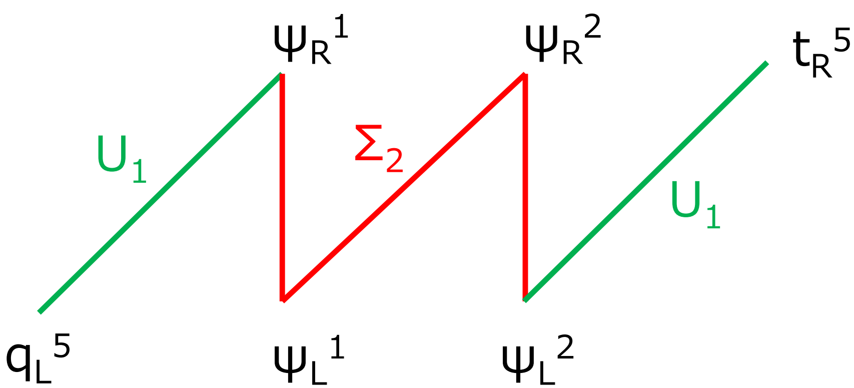
$$\boxed{+(\Delta_L^I \bar{q}_L^5 U_1 \Psi_R^I + \Delta_R^I \bar{t}_R^5 U_1 \Psi_L^I + \text{h.c.})}$$

Mixing

$$\boxed{+\bar{\Psi}^I i\not{D}\, \Psi^I - (\bar{\Psi}_L^I M_\Psi^{IJ} \Psi_R^J + Y^{IJ} \bar{\Psi}_L^I (\Sigma_2 \Sigma_2^T) \Psi_R^J + \text{h.c.})}$$

Strong Sector

- Left-Right structure: One of the solutions to get div. free potential

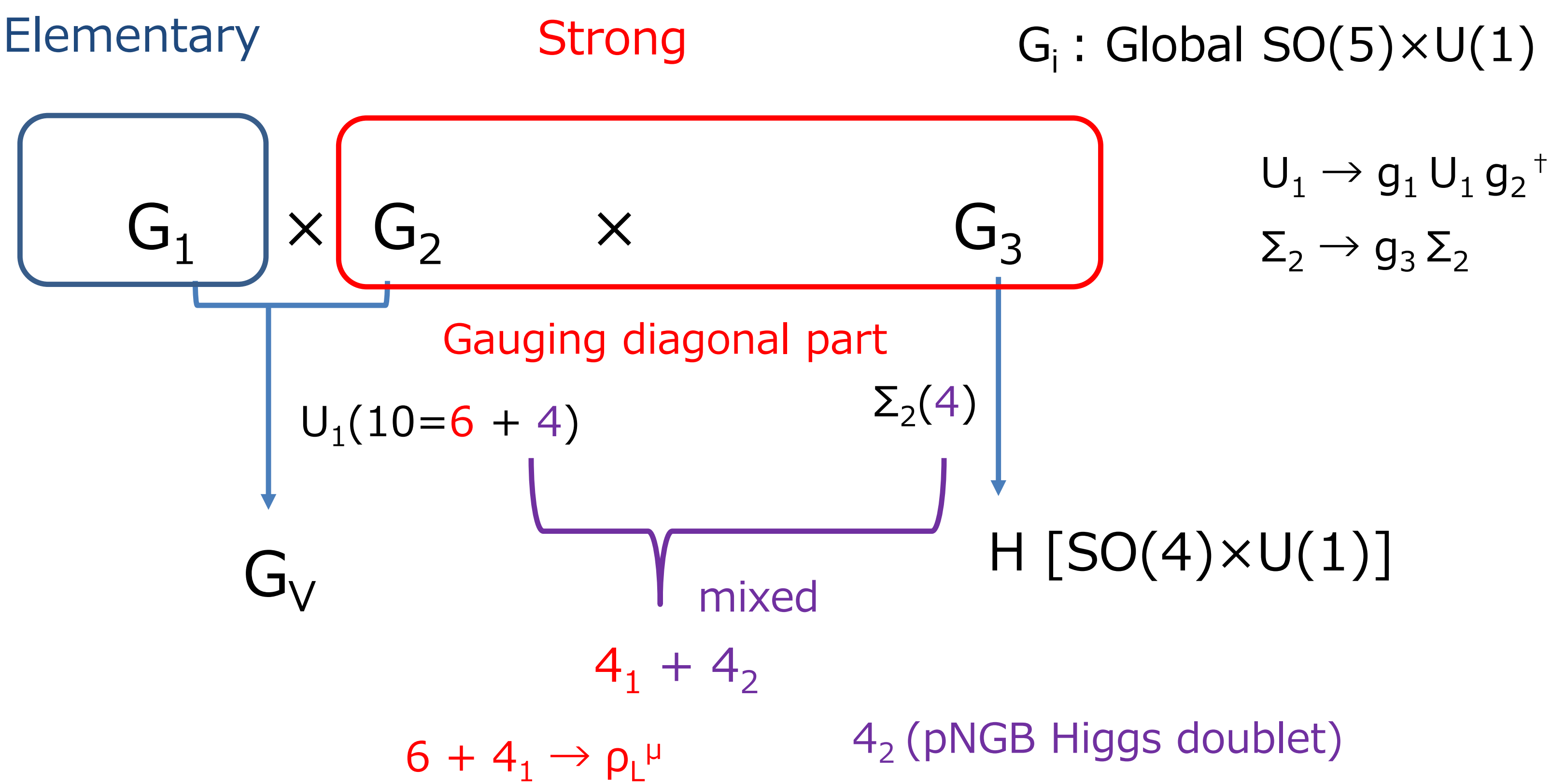


2 flavour case (I, J=1,2)
→ Minimal choice for
UV div. free potential.

$$Y^{21} = M_\Psi^{21} = \Delta_L^2 = \Delta_R^1 = 0$$

Explicit Realization: 2-site model

De Curtis, Redi, Tesi, JHEP04 (2012) 042

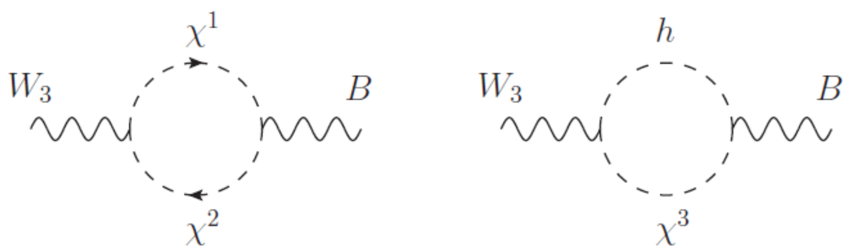


6 + 4 NGBs are absorbed into the longitudinal components of gauge bosons of adj[SO(6)].

S, T parameter

Panico, Wulzer, arXiv:1506.01961

- Contribution from modified Higgs couplings (1-loop)



$$\Delta\widehat{S} = \frac{g^2}{192\pi^2}\xi \log\left(\frac{m_\rho^2}{m_H^2}\right) \simeq 1.4 \times 10^{-3}\,\xi$$

$$\Delta\widehat{T} = -\frac{3g'^2}{64\pi^2}\xi \log\left(\frac{m_\rho^2}{m_H^2}\right) \simeq -3.8 \times 10^{-3}\,\xi\,.$$

Here, $\Lambda = m_\rho = 3$ TeV

$\xi = v^2/f^2$

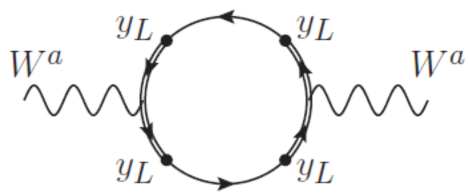
$\xi < 0.05$ @2σ (0.08 @3σ) $f < 1.1$TeV @2σ (870 GeV @3σ)

S, T parameter

Panico, Wulzer, arXiv:1506.01961

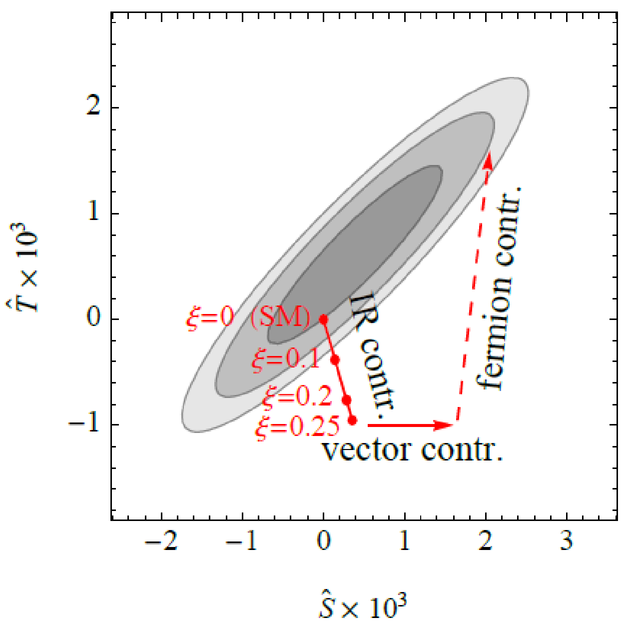
- Contribution from heavy resonances

$$\Delta\widehat{S} = \frac{g_0^2}{2\widetilde{g}_\rho^2}\xi \simeq \frac{m_W^2}{m_\rho^2}$$



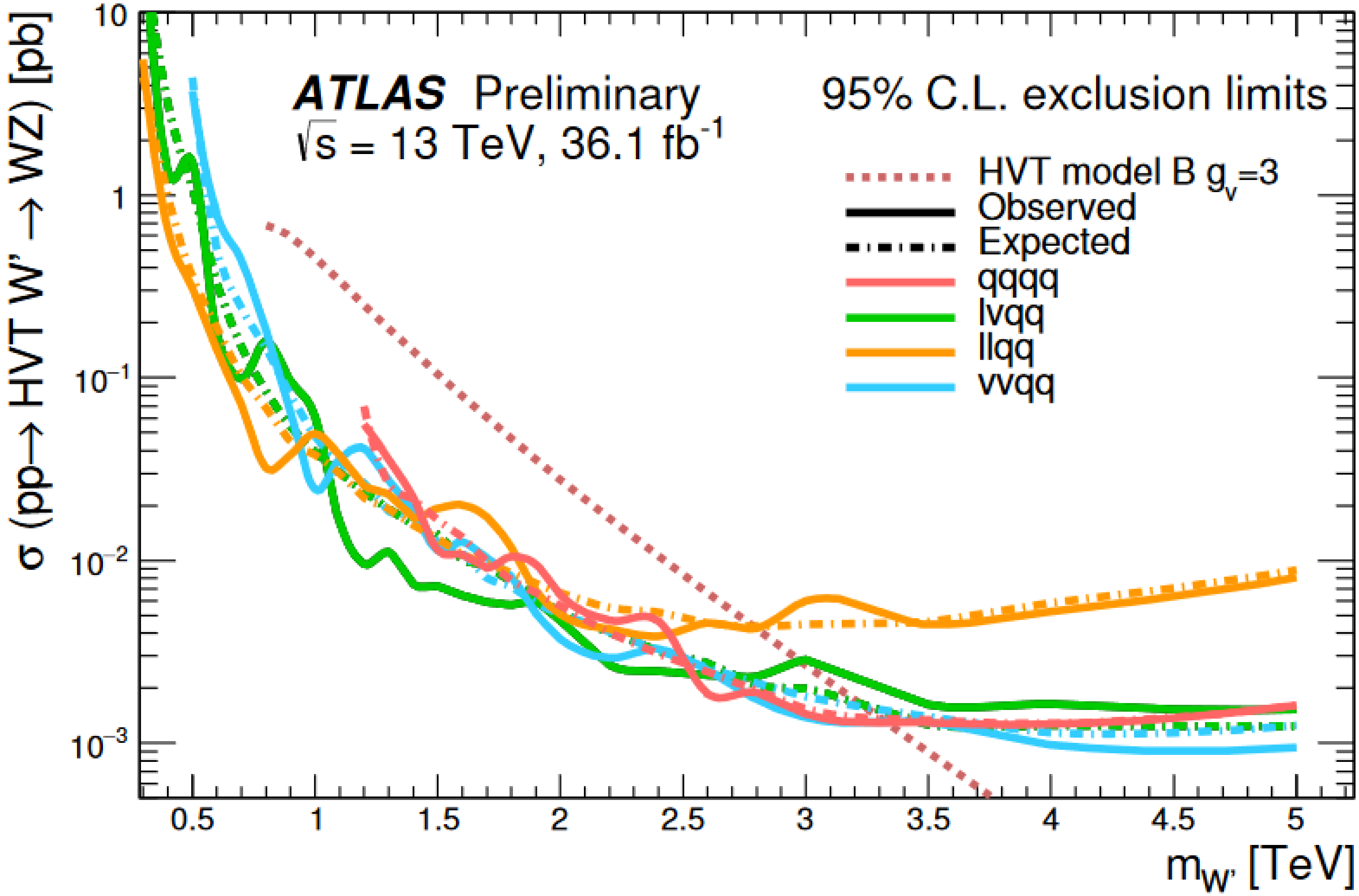
$$\Delta\widehat{T} \simeq \frac{N_c}{16\pi^2}\frac{y_L^4 f^2}{m^2}\xi$$

$y_L = \Delta_L/f$, m : lightest fermion partner mass



Direct search constraint

ATL-PHYS-PROC-2017-114



Numerical Analysis

Input parameters (to be scanned):

$f, \; g_\rho, \; Y_1 \;, \; Y_2 \;, \; \Delta_L, \; \Delta_R, \; M_\Psi, \; M_\Psi^{12}$

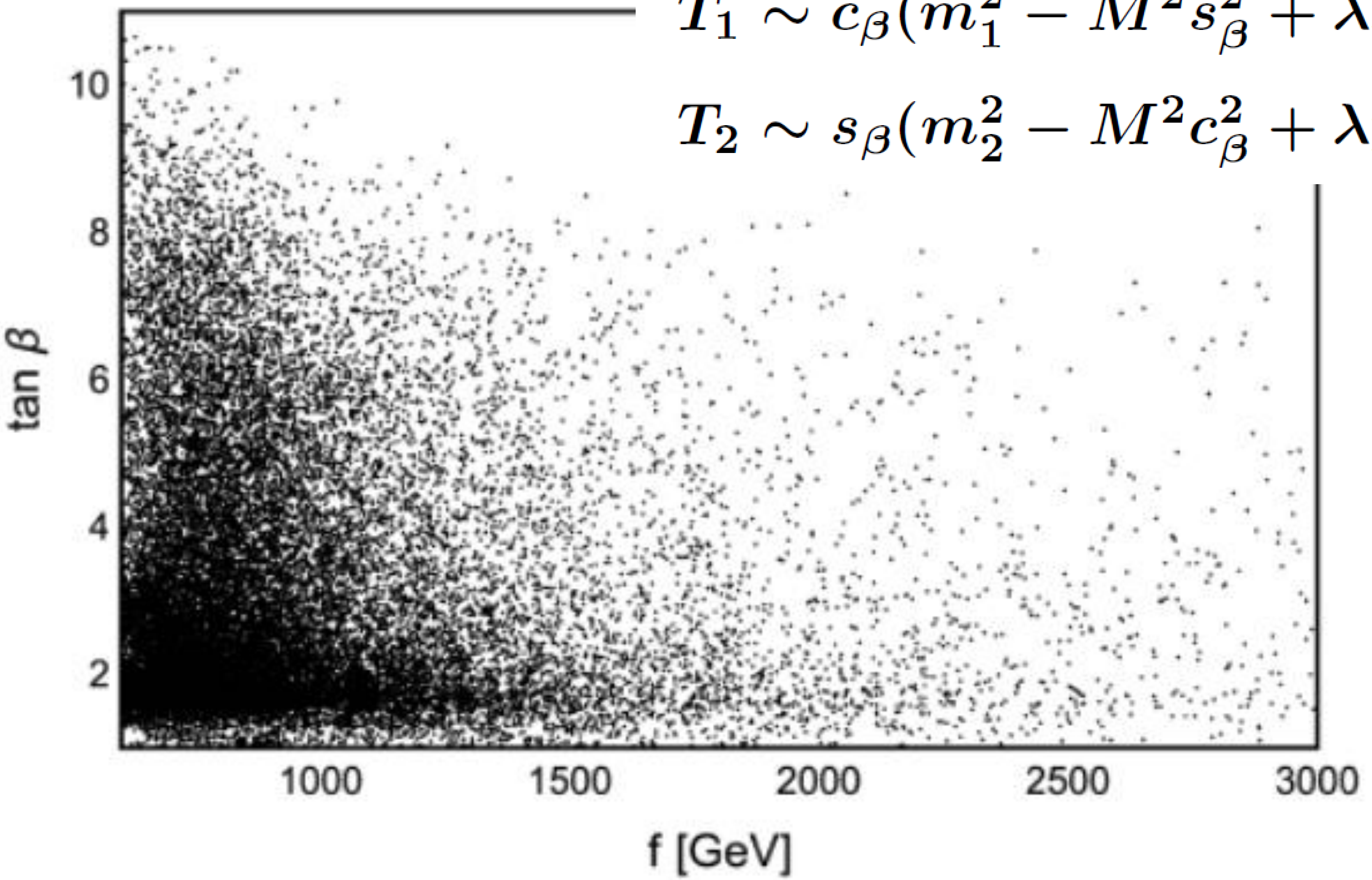
Tadpole conditions: $T_1 = T_2 = 0$

165 GeV < m_t < 175 GeV

120 GeV < m_h < 130 GeV

f VS tanβ

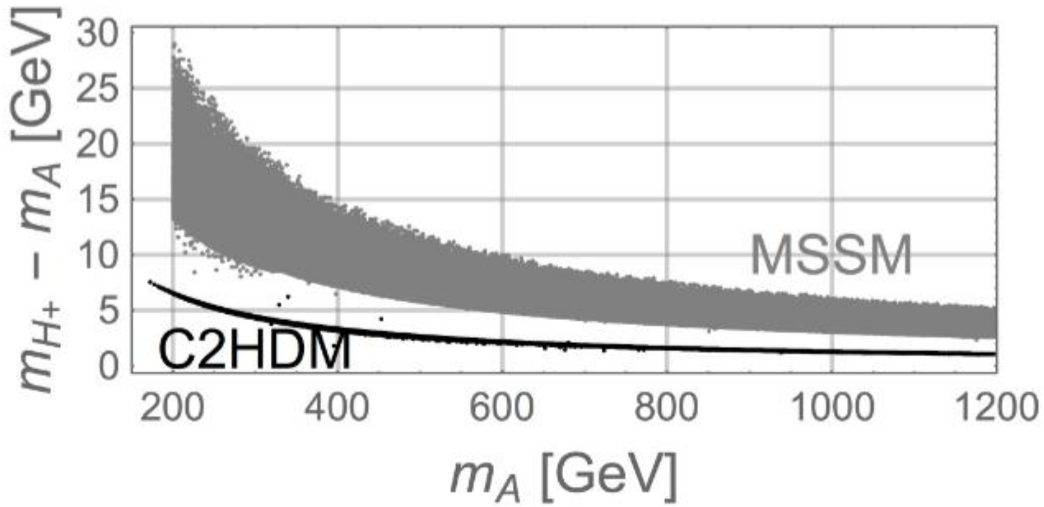
De Curtis, Delle Rose, Moretti, KY, arXiv: 1803.01865 [hep-ph]

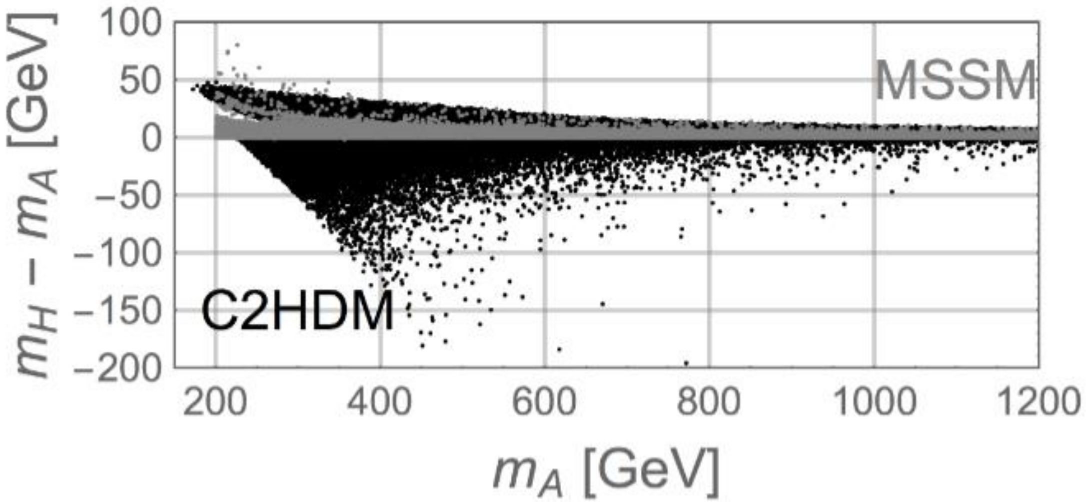


$$T_1 \sim c_\beta(m_1^2 - M^2 s_\beta^2 + \lambda_i v^2)$$

$$T_2 \sim s_\beta(m_2^2 - M^2 c_\beta^2 + \lambda_i' v^2)$$

Correlation b/w m_A and mass differences

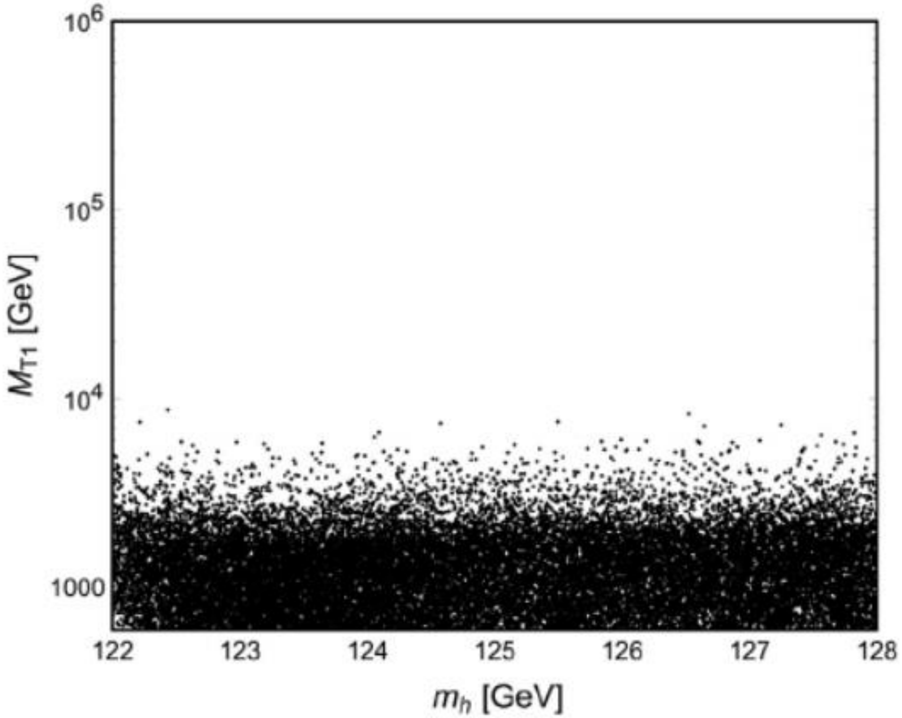




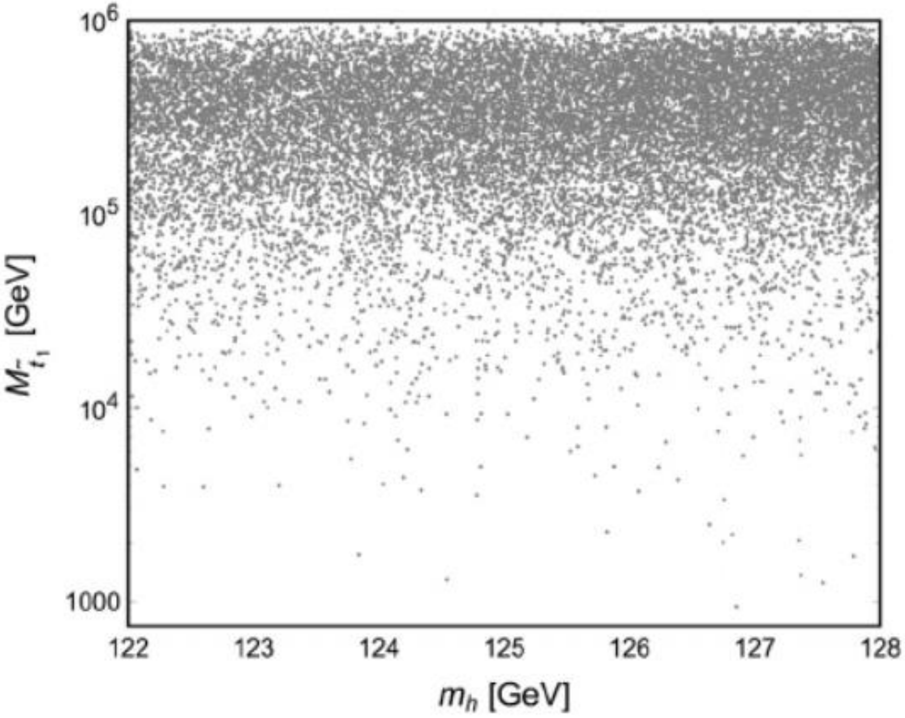
Masses of heavy top partners

De Curtis, Delle Rose, Moretti, KY, arXiv: 1803.01865 [hep-ph]

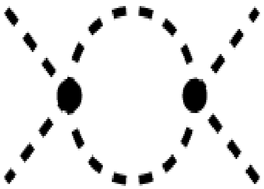
C2HDM



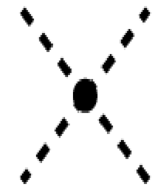
MSSM



Naïve Dimensional Analysis



$$\sim \int \bar{d}^4k \left(\frac{p^2k^2}{f^4}\right)\frac{1}{k^4} \sim \frac{\Lambda^2 p^2}{16\pi^2 f^4}. \sim$$



$$\times \frac{\Lambda^2}{16\pi^2 f^2},$$

Effective Lagrangian (Fermion)

Kanemura, Kaneta, Machida, Shindou, PRD91 (2014) 115016

Model	κ_V	c_{hhVV}	κ_{hhh}	c_{hhhh}	κ_t	κ_b	c_{hhtt}	c_{hhbb}
MCHM_4	$\sqrt{1-\xi}$	$1-2\xi$	$\sqrt{1-\xi}$	$1-\frac{7}{3}\xi$	$\sqrt{1-\xi}$	$\sqrt{1-\xi}$	$-\xi$	$-\xi$
MCHM_5	$\sqrt{1-\xi}$	$1-2\xi$	$\frac{1-2\xi}{\sqrt{1-\xi}}$	$\frac{1-28\xi/3+28\xi^2/3}{1-\xi}$	$\frac{1-2\xi}{\sqrt{1-\xi}}$	$\frac{1-2\xi}{\sqrt{1-\xi}}$	-4ξ	-4ξ
MCHM_{10}	$\sqrt{1-\xi}$	$1-2\xi$	$\frac{1-2\xi}{\sqrt{1-\xi}}$	$\frac{1-28\xi/3+28\xi^2/3}{1-\xi}$	$\frac{1-2\xi}{\sqrt{1-\xi}}$	$\frac{1-2\xi}{\sqrt{1-\xi}}$	-4ξ	-4ξ
MCHM_{14}	$\sqrt{1-\xi}$	$1-2\xi$	H_1	H_2	F_3	$\frac{1-2\xi}{\sqrt{1-\xi}}$	F_6	-4ξ
$\mathrm{MCHM}_{5\text{-}5\text{-}10}$	$\sqrt{1-\xi}$	$1-2\xi$	$\frac{1-2\xi}{\sqrt{1-\xi}}$	$\frac{1-28\xi/3+28\xi^2/3}{1-\xi}$	$\frac{1-2\xi}{\sqrt{1-\xi}}$	$\sqrt{1-\xi}$	-4ξ	$-\xi$
$\mathrm{MCHM}_{5\text{-}10\text{-}10}$	$\sqrt{1-\xi}$	$1-2\xi$	$\frac{1-2\xi}{\sqrt{1-\xi}}$	$\frac{1-28\xi/3+28\xi^2/3}{1-\xi}$	$\sqrt{1-\xi}$	$\sqrt{1-\xi}$	$-\xi$	$-\xi$
$\mathrm{MCHM}_{5\text{-}14\text{-}10}$	$\sqrt{1-\xi}$	$1-2\xi$	H_1	H_2	F_5	$\sqrt{1-\xi}$	F_8	$-\xi$
$\mathrm{MCHM}_{10\text{-}5\text{-}10}$	$\sqrt{1-\xi}$	$1-2\xi$	$\frac{1-2\xi}{\sqrt{1-\xi}}$	$\frac{1-28\xi/3+28\xi^2/3}{1-\xi}$	$\sqrt{1-\xi}$	$\frac{1-2\xi}{\sqrt{1-\xi}}$	$-\xi$	-4ξ
$\mathrm{MCHM}_{10\text{-}14\text{-}10}$	$\sqrt{1-\xi}$	$1-2\xi$	H_1	H_2	$\frac{1-2\xi}{\sqrt{1-\xi}}$	$\frac{1-2\xi}{\sqrt{1-\xi}}$	-4ξ	-4ξ
$\mathrm{MCHM}_{14\text{-}1\text{-}10}$	$\sqrt{1-\xi}$	$1-2\xi$	$\frac{1-2\xi}{\sqrt{1-\xi}}$	$\frac{1-28\xi/3+28\xi^2/3}{1-\xi}$	$\frac{1-2\xi}{\sqrt{1-\xi}}$	$\frac{1-2\xi}{\sqrt{1-\xi}}$	-4ξ	-4ξ
$\mathrm{MCHM}_{14\text{-}5\text{-}10}$	$\sqrt{1-\xi}$	$1-2\xi$	H_1	H_2	F_4	$\frac{1-2\xi}{\sqrt{1-\xi}}$	F_7	-4ξ
MC								
MC								

Fingerprinting is possible among various MCHMs!

Effective Lagrangian (Gauge)

$$\mathcal{L}_{\rm eff} \supset \frac{P_T^{\mu\nu}}{2}[\Pi_0(p^2)A_\mu^A A_\nu^A + \Pi_1(p^2)\Sigma^T A_\mu^A A_\nu^A \Sigma]$$

$$\xrightarrow[\Sigma\to\Sigma_0]{} \frac{P_T^{\mu\nu}}{2}[\underbrace{\Pi_0(p^2)}_{-\frac{p^2}{g_A^2}+\frac{m_\rho^2 p^2}{g_\rho^2(p^2-m_\rho^2)}}A_\mu^a A_\nu^a + \underbrace{[\Pi_0(p^2)+\tfrac{1}{2}\Pi_1(p^2)]}_{-\frac{p^2}{g_A^2}+\frac{m_\rho^2[p^2-(m_{\hat\rho}^2-m_\rho^2)]}{g_\rho^2(p^2-m_{\hat\rho}^2)}}A_\mu^{\hat a} A_\nu^{\hat a}]$$

2-site model

$$\mathcal{L}_{\rm eff} \xrightarrow[A_\mu^A\to W_\mu^a]{} \frac{P_T^{\mu\nu}}{2}[\Pi_0(p^2)+\tfrac{1}{4}\Pi_1(p^2)\sin^2\tfrac{\phi}{f}]W_\mu^a W_\nu^a$$

$$= \frac{P_T^{\mu\nu}}{2}[p^2\underbrace{\Pi_0(0)'}_{1/g^2} + \tfrac{1}{4}\underbrace{\Pi_1(0)\sin^2\tfrac{\phi}{f}}_{v_{sm}^2}]W_\mu^a W_\nu^a + \cdots$$

Consistent with the NLΣM

Effective Lagrangian (Fermion)

$$\mathcal{L}_{\text{eff}} \supset \bar{q}^5_L[M_0(p^2) + M_1(p^2)\Sigma\Sigma^T]t^5_R + \text{h.c.}$$ (+ LL-term + RR-term)

$$\xrightarrow[\substack{q^5_L \to q_L \\ t^5_R \to t_R}]{} \frac{\sin\frac{\phi}{f}\cos\frac{\phi}{f}}{\sqrt{2}}\bar{q}_L M_1(p^2)\hat{\Phi}t_R + \text{h.c.} \qquad \hat{\Phi} = \frac{1}{\phi}\Phi$$

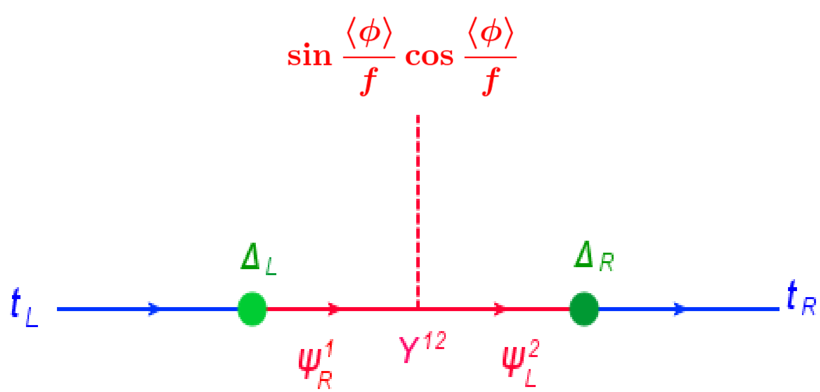
2-site model

$$M_1(p^2) = F(M^{11}_\Psi, M^{22}_\Psi, M^{12}_\Psi) - F(M^{11}_\Psi, M^{22}_\Psi, M^{12}_\Psi + Y^{12})$$

$$F(m_1, m_2, m_3) = -\frac{\Delta_L\Delta_R m_1 m_2 m_3}{(p^2 - m_1^2)(p^2 - m_2^2) - p^2 m_3^2}$$

$$m_t \xrightarrow[p^2 \to 0]{} \frac{s_{\langle\phi\rangle/f}\, c_{\langle\phi\rangle/f}}{\sqrt{2}} \frac{\Delta_L\Delta_R Y^{12}}{M^{11}_\Psi M^{22}_\Psi}$$

$$g_{ht\bar{t}}/g^{\text{SM}}_{ht\bar{t}} = \frac{1-2\xi}{\sqrt{1-\xi}} \qquad \xi = \frac{\langle\phi\rangle^2}{f^2}$$



Composite 2HDMs

- G/H: SO(6)/SO(4)×SO(2), SU(5)/SU(4)×U(1), Sp(6)/Sp(4)×SU(2), SO(9)/SO(8)

  → 8 NGBs

- Previous works:

  Mrazek, Pomarol, Rattazi, Redi, Serra, Wulzer NPB 853 (2011) 1-48

  ・Possible G invariant operators classified by the spurion technique in the SO(6)/SO(4)×SO(2) model.

  De Curtis, Delle Rose, Moretti, KY, arXiv: 1803.01865 [hep-ph]

  ・2-site model is implemented in the SO(6)/SO(4)×SO(2) model

- Z_2-like symmetry in the strong sector

  ・Unbroken (Dark Matter)

  ・Spontaneously broken (No FCNC; light extra Higgses)

  ・Hardly broken: (Yukawa Alignment; heavy extra Higgses)