WW scattering in a radiative electroweak symmetry breaking scenario

[KE, K. Ishiwata and Y. Sumino, 1601.00696 (PRD)]

Kazuhiro Endo[(a)], Koji Ishiwata[(b)] and Yukinari Sumino[(a)]

[(a)]Department of Physics, Tohoku University

[(b)]Institute for Theoretical Physics, Kanazawa University

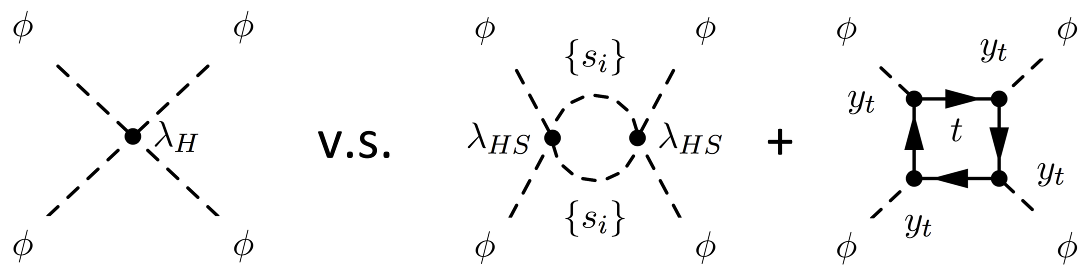
- In a classically scale-invariant (CSI) SM with singlet scalars, electroweak-symmetry breaking (EWSB) is induced via Coleman-Weinberg (CW) -type potential and Higgs self-coupling is enhanced.
- $W_L W_L$-scattering can be a good probe for the enhanced coupling.
- "ξ-expansion" is introduced for systematic perturbation, ensuring special order-counting.

1. Model and analysis method

$$\mathscr{L} = \mathscr{L}_{\rm SM}|_{\mu_H=0} + \frac{1}{2}(\partial_\mu \vec{S})^2 - \lambda_{HS}(H^\dagger H)(\vec{S}\cdot\vec{S}) - \frac{\lambda_S}{4}(\vec{S}\cdot\vec{S})^2$$

- ✧ EWSB via CW mechanism
- ✧ Singlet scalar S as global-$O(N)$ multiplet.
- ✧ Tree effect contributes at the same order as 1-loop effects.
  –> Special order-counting

$$V_{\rm eff} = \frac{\lambda_H}{4}\phi^4 + \frac{N\lambda_{HS}{}^2}{64\pi^2}\phi^4 \ln\left(\frac{\phi^2}{v^2}\right) - \frac{N_C y_t{}^4}{64\pi^2}\phi^4 \ln\left(\frac{\phi^2}{v^2}\right)$$



$$\longrightarrow |\lambda_{\rm H}| \sim \frac{N\,\lambda_{\rm HS}{}^2}{(4\pi)^2} - \frac{N_C\,y_t{}^4}{(4\pi)^2} \ll 1$$

<– perturbative validity

- ✧ Auxiliary expansion parameter ξ for systematic perturbation.
  –> The counting is ensured in each order.
  (e.g.) quantity $A(\xi)$ of $O(\xi^n)$
  $A(\xi) = \xi^n(a_0 + \xi a_1 + \xi^2 a_2 + \cdots)$

$\lambda_H \to \xi^2 \lambda_H$

$\lambda_{HS} \to \xi\,\lambda_{HS} \quad y_t \to \xi^{1/2} y_t$

Order	Parameters	
ξ^1	$\lambda_{HS},\ y_t^2$	$m_s^2,\ m_t^2$
ξ^2	$\lambda_{HS}^2,\ y_t^4,\ \lambda_H$	m_h^2

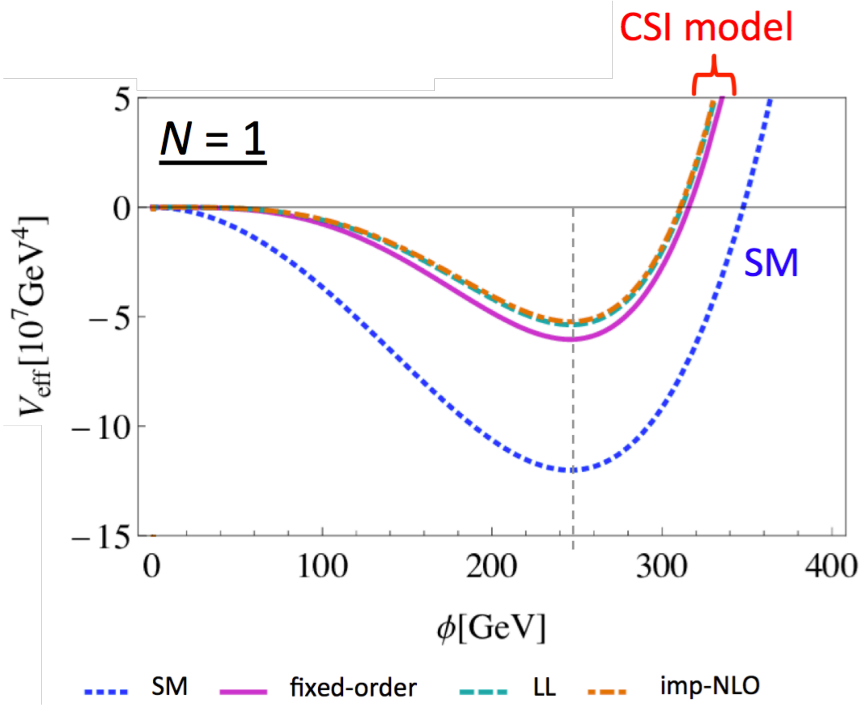
2. Vacuum structure as scalar couplings

- ✧ EWSB is induced at $O(\xi^2)$
  [= LO of EWSB].
  –> Hereafter analyse up to $O(\xi^2)$.

$$\left.\frac{\partial V_{\rm eff}}{\partial\phi}\right|_{\phi=246{\rm GeV}} = 0$$

$$\left.\frac{\partial^2 V_{\rm eff}}{\partial\phi^2}\right|_{\phi=246{\rm GeV}} = (126\ {\rm GeV})^2$$

$\lambda_S = 0.1$ (barely dependent)



- ❖ Large λ_{HS}, but still in perturbative regime.
- ❖ (Singlet VEV) = 0 –> unbroken $O(N)$
- ❖ Singlet is stable. –> dark matter
- ❖ Substantial parameters: (λ_H, λ_{HS}).

	$N=1$	$N=4$	$N=12$
SM couplings (except λ_H) unchanged.			
$\lambda_H(v)$	-0.11	-0.0045	0.075
$\lambda_{HS}(v)$	4.8	2.4	1.4
$\langle\varphi\rangle$	0	0	0
m_s [GeV]	556	378	285

- ✧ Couplings among the scalars
  Taylor series around the vacuum:

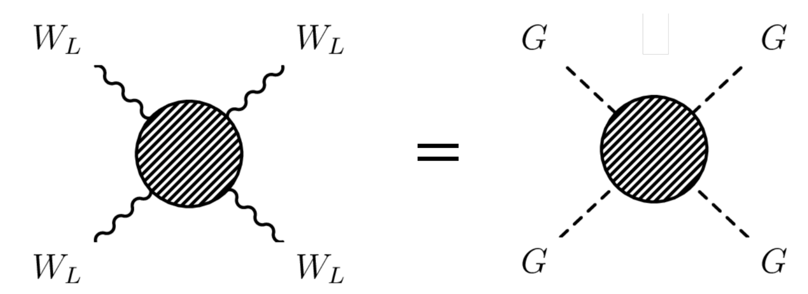
$$V_{\rm eff} = {\rm const.} + \frac{1}{2}m_h{}^2 h^2 + \frac{1}{2}m_s{}^2\,\vec{s}\cdot\vec{s} + \frac{\lambda_{hhh}}{3!}vh^3 + \frac{\lambda_{hhhh}}{4!}h^4 + \frac{\lambda_{hss}}{2}v\,h\,\vec{s}\cdot\vec{s} + \frac{\lambda_{hhss}}{4}h^2\,\vec{s}\cdot\vec{s} + \frac{\lambda_{ssss}}{4!}(\vec{s}\cdot\vec{s})^2 + \ldots$$

- ❖ Higgs self-couplings enhance due to the characteristic potential structure.
- ❖ The other couplings are relatively large.

	$N=1$	$N=4$	$N=12$
$\lambda_{hhh}/\lambda_{hhh}^{\rm (SM)}$	1.8	1.7	1.6
$\lambda_{hhhh}/\lambda_{hhhh}^{\rm (SM)}$	4.3	3.2	2.8
λ_{hss}	10	5.0	3.0
λ_{hhss}	13	5.7	3.2
λ_{ssss}	6.5	1.9	0.9

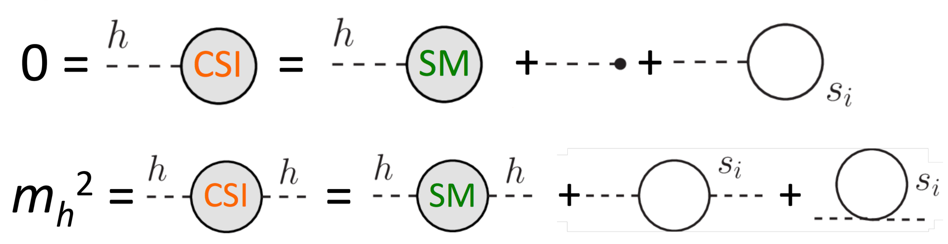
3. $W_L W_L$-scattering

- ✧ Goldstone-boson self-coupling also enhances.
  –> *Vector-boson scattering becomes a good probe* at high-energy [*Equivalence theorem*].
- ✧ One of the main targets of the 2[nd] run of LHC.



at $E << M_W$

- ✧ To take wider kinematical region into account, apply ξ-expansion to Feynman rules; determine parameters and check their consistency up to $O(\xi^2)$.



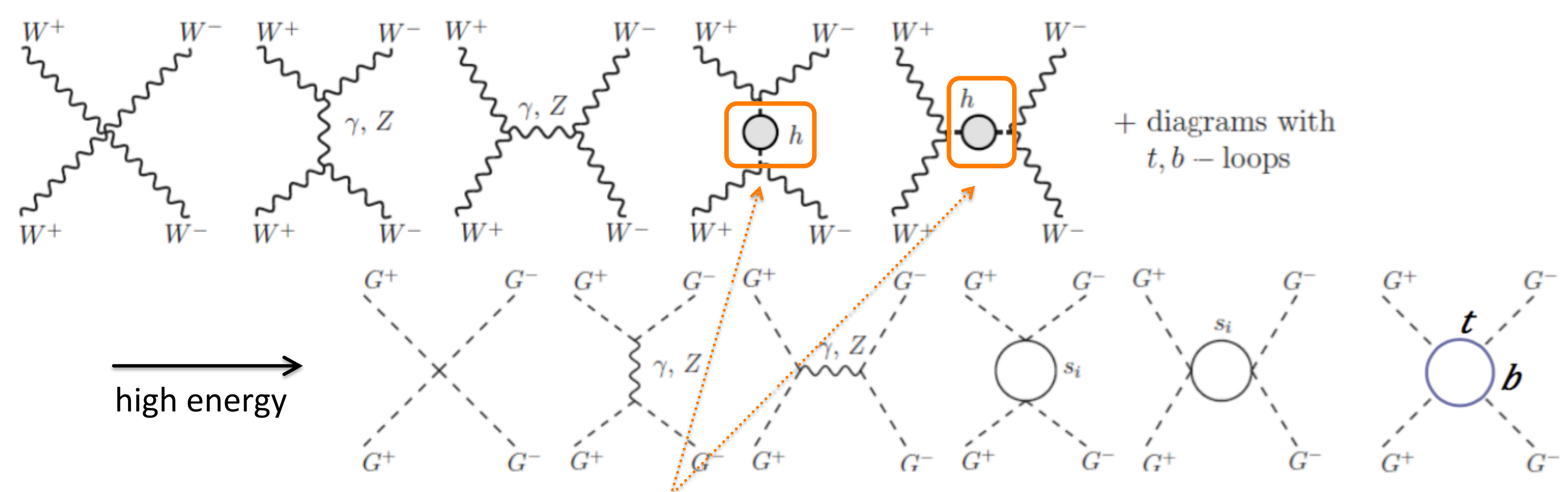
$$\leftrightarrow \left.\frac{\partial V_{\rm eff}}{\partial\phi}\right|_{\phi=246{\rm GeV}} = 0$$

$$\leftrightarrow \left.\frac{\partial V_{\rm eff}}{\partial\phi}\right|_{\phi=246{\rm GeV}} = (126\ {\rm GeV})^2$$

N	1	4	12
$\lambda_{\rm HS}(\mu \simeq 2m_s)$	4.82	2.41	1.39
m_s [GeV]	541	383	291

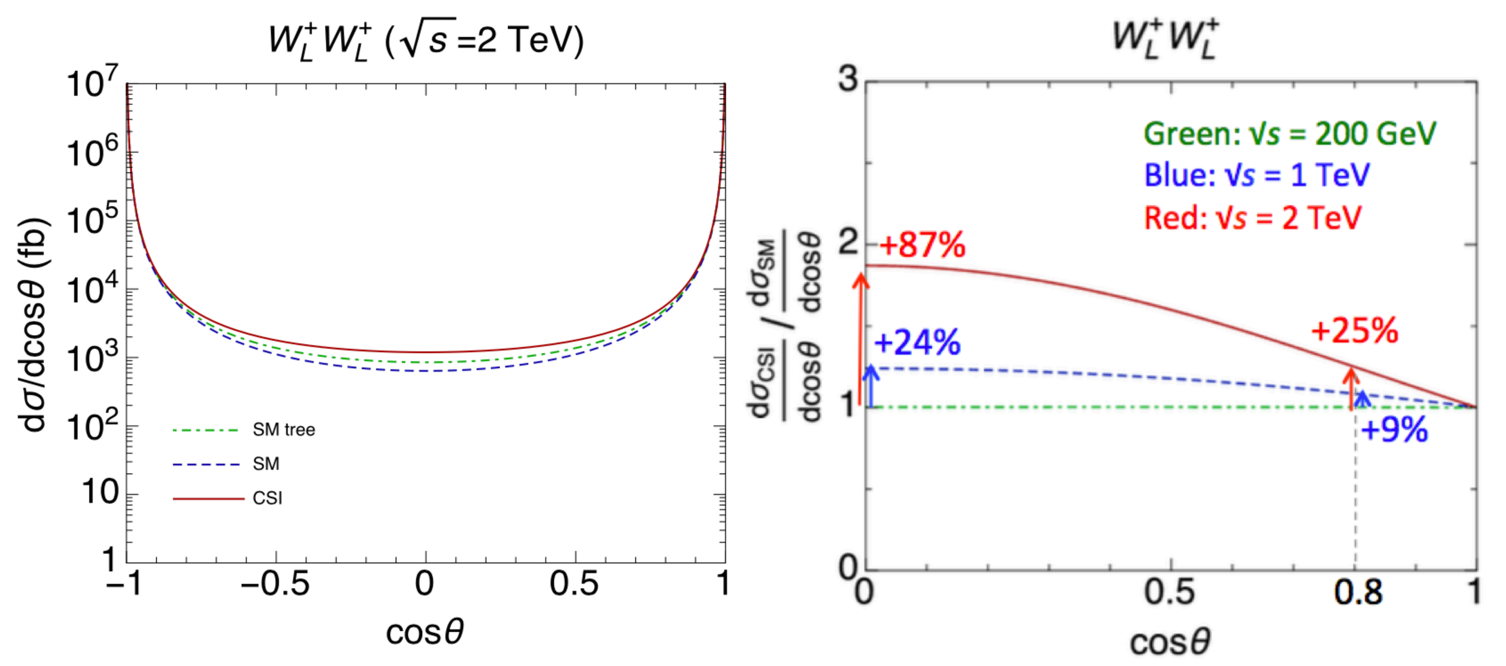
✓ Consistent with effective-potential analysis

- ✧ In N = 1 case for $W_L^+W_L^+$- and $W_L^+W_L^-$-scatterings, we calculate scattering amplitudes and differential cross sections.



- ❖ BSM (singlet) effect appears as off-shell-Higgs effect.
  [Technically, just replacing Higgs propagator: SM <–> CSI]
- ❖ Amplitudes' behaviour: ✓ Equivalence theorem
  ✓ Gauge cancellation

- ✧ Cross sections enhance: at √s = 2 TeV,
  $W_L^+W_L^+$ –> deviates 87% (25%) at cosθ = 0 (0.8)
  $W_L^+W_L^-$ –> deviates 90% (29%) at cosθ = 0.5 (0.8)



4. Conclusion

- ✧ In $W_L W_L$-scattering, deviation from SM prediction is 90% at cosθ ~ 0 and 25% at forward region.
- ✧ By virtue of ξ-expansion, BSM contribution is correctly considered; equivalence theorem and gauge cancellation are satisfied.