LHC and Vector Boson Scatterings

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Introduction

LHC and TeV Era

LEP II, SLD, and the Tevatron have checked/been checking the SM below 200 300 GeV or so, and the SM works quite well to explain all data LHC, which will have pp collision at a center-of-mass energy of 14 TeV and a design luminosity of $L = 10^{34}\,cm^{-2}\,s^{-1}$, is believed to have the potential to discover the EWSB (Higgs, SUSY particles, technicolor, or extra dimensions).

Electroweak Symmetry Breaking Mechanism

Although the SM has owned the unprecedented success, the electroweak symmetry breaking sector of it is still elusive. While according to the Nambu-Goldstone theorem, for the electroweak symmetry breaking, the singlet scalar Higgs in the minimal linear realization in the SM is not necessary. So the 4D Higgsless electroweak chiral Lagrangian without including a scalar Higgs is the minimal model consistent with Nambu-Goldstone theorem.

Why vector boson scatterings are important at LHC?

There are several possible situations that might occur at future LHC:

- LHC might find plenty of resonances, like the low energy hadronic QCD case. Then, how to understand these resonances is a problem. Do they mean the strong interaction (these resonances are just like mesons and baryons), or SUSY (superparticles), or extra dimensions (KK excitations of the SM particles)? In this case, we need consider vector boson scatterings to help us reveal the underlying theory for these resonances.
- LHC might only find one resonance (maybe few resonances). Besides to measure its center mass, decay width, spin, parity, and scattering, the study of vector boson scattering is still necessary to confirm or exclude its strong interaction origin.
- LHC might detect no resonance. Then the study of vector boson scattering processes is absolutely necessary to probe the EWSB mechanism

So, for any case in the future, the study of vector boson scattering is quite important to confer a no-losecapability to discover the EWSB mechanism.

CMS and vector boson scattering [1]

In the detector CMS, triple gauge couplings be detected via various processes: $qq \to qqW(W \to \ell^{\pm}\nu)$ and $qq \to qqZ(Z \to \ell^+\ell^-)$, where $\ell = e\,\mu$. And the quadruple gauge couplings can detected via processes: $qq \to qqVV$. The most important process is $W_L W_L \to W_L W_L$, according to the equivalent theorem, which is Goldstones scattering process and are believed to be very sensitive the EWSB. A typical Feynman diagram for vector boson scattering processes at LHC is given as:

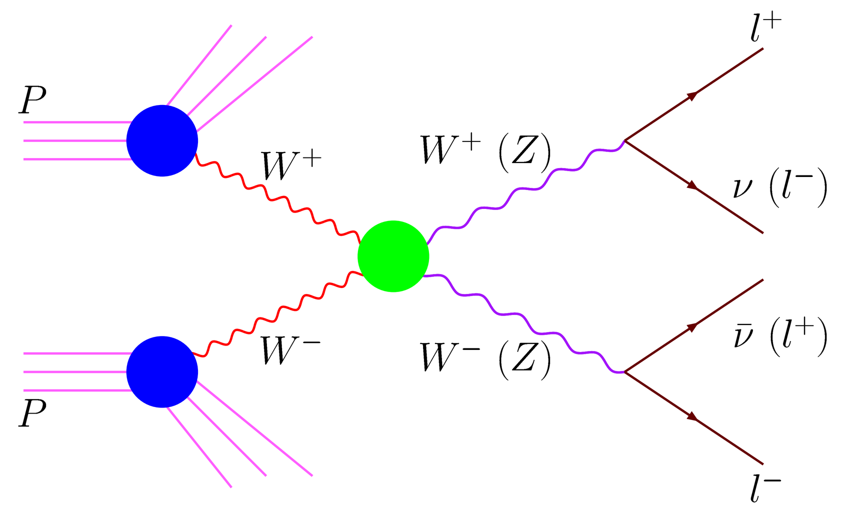


Figure 1: Typical vector boson scattering process in LHC

Theoretical framework

The 4D Higgsless electroweak chiral Lagrangian should only include the vector bosons (A, Z, and $W^{\pm}$) and their corresponding Goldstone (ξ_Z and $\xi_W^{\pm}$) as the active degrees of freedom.

Form Factor V.S. 4D Higgsless Model

The pure phenomenological method is to construct the form factors for various vector boson scattering processes. The quadratic vector interaction form factor can be described by S, T, U, W, X, ans Y [2]. The triple vector interaction form factors can be formulated as [3]

$$\begin{aligned}\mathcal{L}_{WWV} = g_{WWV}\Big[& ig_1^V V_\mu (W^{-,\nu} W^+_{\mu\nu} - W^-_{\mu\nu} W^{+,\nu}) \\ & + i k_V W^-_\mu W^+_\nu V^{\mu\nu} + i\frac{\lambda_V}{m_W^2} W^{-,\nu}_\mu W^{+,\rho}_\nu V^\mu_\rho \\ & + g_5^V \epsilon^{\mu\nu\rho\sigma}(W^-_\mu \partial_\rho W^+_\nu - \partial_\rho W^-_\mu W^+_\nu) V_\sigma\Big] \qquad (1)\end{aligned}$$

While for the four vector scattering processes, the number of independent form factors increases quickly.

4D Higgsless electroweak Chiral Lagrangian is constructed in a more systematic and consistent way. It is a bottom-up approach. The advantage of this approach is that it is a model independent method. But the drawback of it is that the theory is not renormalizable with limitted operators. The electroweak chiral Lagrangian [4] can be formulated as

$$\mathcal{L}_{EW} = \mathcal{L}_{EW}^{p^2} + \mathcal{L}_{EW}^{p^4} + \cdots \qquad (2)$$

$$\mathcal{L}_{EW}^{p^2} = \mathcal{L}_B\,, \qquad (3)$$

$$\mathcal{L}_{EW}^{p^4} = \beta\mathcal{L}_0 + \sum_{i=1}^{10}\alpha_i\mathcal{L}_i \qquad (4)$$

where

$$\mathcal{L}_B = -H_1 - H_2 + \mathcal{L}_{WZ}\,, \qquad (5)$$

$$H_1 = \frac{1}{4g^2} W^a_{\mu\nu} W^{a\mu\nu}\,, \qquad (6)$$

$$H_2 = \frac{1}{4g'^2} B_{\mu\nu} B^{\mu\nu}\,, \qquad (7)$$

$$\mathcal{L}_{WZ} = \frac{v^2}{4} tr(V\cdot V)\,, \qquad (8)$$

$$\mathcal{L}_0 = \frac{v^2}{8}[tr(\mathcal{T}V_\mu)]^2\,, \qquad (9)$$

$$\mathcal{L}_1 = i\frac{1}{2} B_{\mu\nu} tr(\mathcal{T} W^{\mu\nu})\,, \qquad (10)$$

$$\mathcal{L}_2 = i\frac{1}{2} B_{\mu\nu} tr(\mathcal{T}[V^\mu, V^\nu])\,, \qquad (11)$$

$$\mathcal{L}_3 = i1 tr(W_{\mu\nu}[V^\mu, V^\nu])\,, \qquad (12)$$

$$\mathcal{L}_4 = [tr(V_\mu V_\nu)]^2\,, \qquad (13)$$

$$\mathcal{L}_5 = [tr(V_\mu V^\mu)]^2\,, \qquad (14)$$

$$\mathcal{L}_6 = tr(V_\mu V_\nu) tr(\mathcal{T}V^\mu) tr(\mathcal{T}V^\nu)\,, \qquad (15)$$

$$\mathcal{L}_7 = tr(V_\mu V^\mu)[tr(\mathcal{T}V^\nu)]^2\,, \qquad (16)$$

$$\mathcal{L}_8 = \frac{1}{4}[tr(\mathcal{T}W_{\mu\nu})]^2\,, \qquad (17)$$

$$\mathcal{L}_9 = i\frac{1}{2} tr(\mathcal{T}W_{\mu\nu}) tr(\mathcal{T}[V^\mu, V^\nu])\,, \qquad (18)$$

$$\mathcal{L}_{10} = [tr(\mathcal{T}V_\mu) tr(\mathcal{T}V_\nu)]^2\,. \qquad (19)$$

where the auxiliary variable V_μ and $\mathcal{T}$ is defined as

$$V_\mu = U^\dagger(\partial_\mu - iW^a_\mu T^a)U + iB_\mu T^3\,. \qquad (20)$$

$$\mathcal{T} = 2U^\dagger T^3 U = U^\dagger \tau^3 U\,, \qquad (21)$$

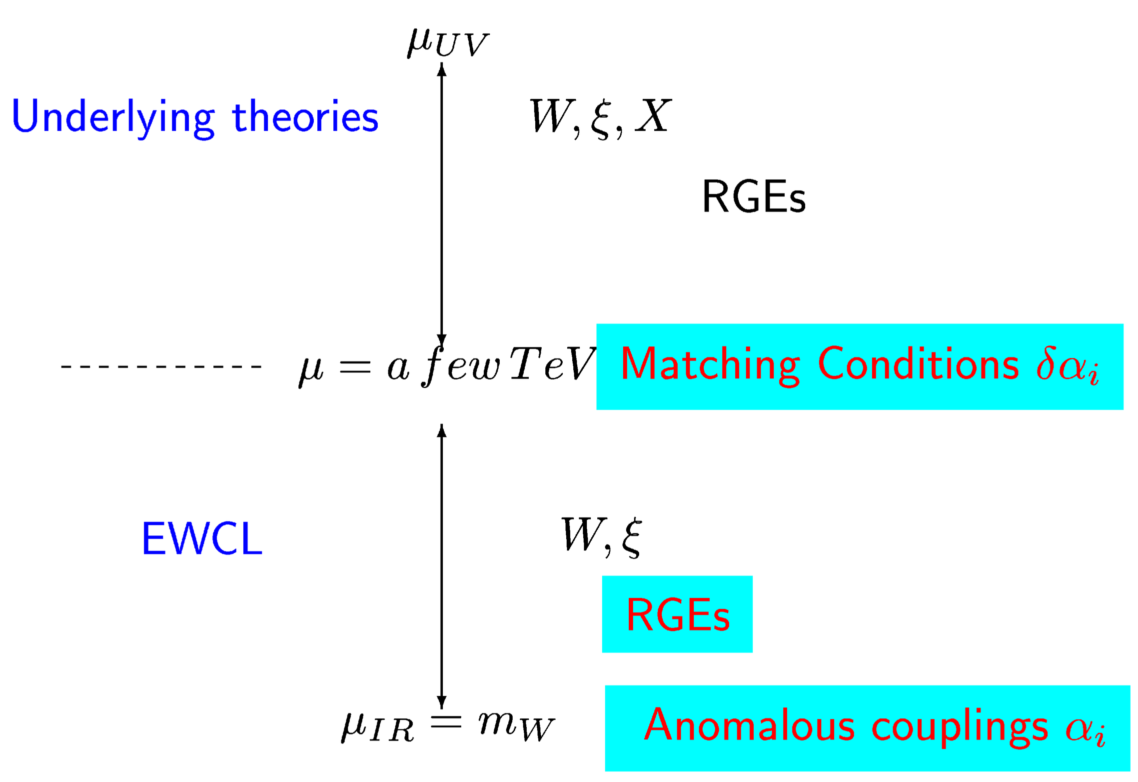
where the τ^3 is the third Pauli matrices. Anomalous couplings α_i form the parameter space of the EWCL.

Global fi t with EWCL

With the accumulation of data, in the near future at Tevatron II, LHC, LC, and NLC, we will confront with the problem as how to consistently interpret vector boson scattering processes. So the global fit with EWCL is necessary.

Road-map for the global fi t with EWCL

The typical pattern for the matching and running in the EWCL is shown as :



RGEs: Integrating the low energy and high energy precision test

RGEs of EWCL [5] can relate anomalous couplings at different renormalization scales. For example, by using the α_1 and α_8 measured at 200 GeV, α_2, α_3, and α_9 measured at 500 GeV, and α_4, α_5, α_6, α_7 and α_{10} measured 1000 GeV, with the help of RGEs we can make global fits with the EWCL, and put constraints on the parameter space of EWCL.

The function of the RGEs includes:

- Integrated global fits with both low energy precision tests (like LEP, and future Giga Z) and high energy precision test (LHC and future LC).
- Pin down the possible effects from $O(p^6)$. For instance, if the prediction of the RGEs is the case 2 as shown in the following figure, then there is no room for the higher order operators. But if the prediction is the case 1 or case 3, the contribution from higher order operators will not be negligible.

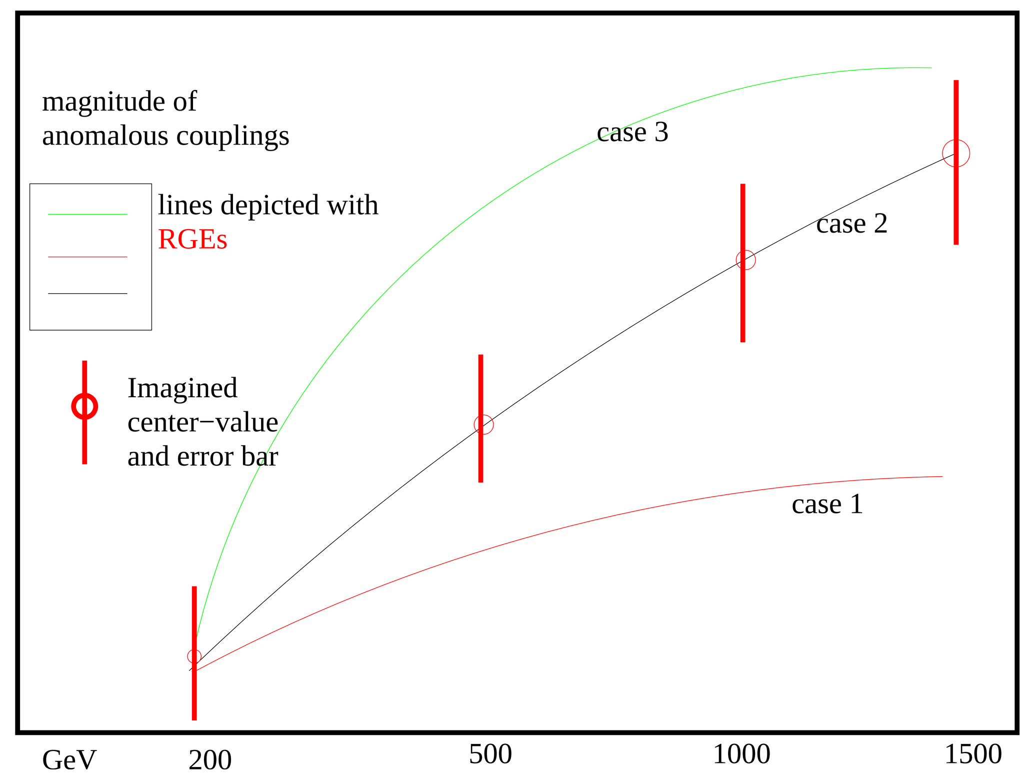


Figure 2: The running behavior of anomalous couplings confronts with the future experiments

A new mechanism for negative S

The RGE running reveals a new mechanism [5] to generate a negative S parameter ($S = -16\pi\alpha_1$) at $\mu = m_Z$.

$$\begin{aligned}8\pi^2\frac{d\alpha_1}{dt} \approx\ & \frac{\rho}{6} - \frac{\rho^2}{12} + 2\alpha_1 g^2 + \frac{\alpha_2 g^2\,(6+\rho)}{2} - \frac{\alpha_3 g^2\,(22+3\rho)}{6} \\ & + \alpha_8 g^2 - \frac{\alpha_9 g^2\,(-4+\rho)}{2}\,. \end{aligned} \qquad (22)$$

The formal solution for $\alpha_1(m_Z)$ can be expressed as

$$\alpha_1(m_Z) = \alpha(\Lambda) + \beta_{\alpha_1}\ln\left(\frac{\Lambda}{m_Z}\right) \qquad (23)$$

this solution tells us that the $\alpha_1(m_Z)$ depends not only on the initial value at $\alpha(\Lambda)$, but also on the sign of its β function and the UV cutoff Λ. According to the current experimental limit, its β function (determined by α_2, α_3, α_9) can be either positive and negative.

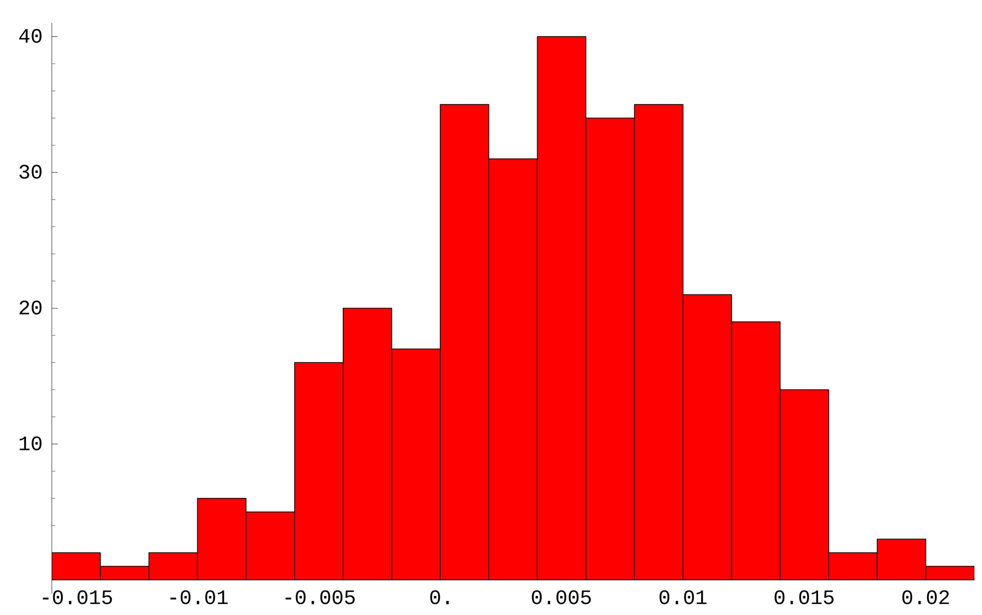


Figure 3: In the solutions of $\alpha(\Lambda)$ with $\Lambda = 1TeV$ which satisfy the current experiment constraints from S ($S = -16\pi\alpha_1$), there are more 50 points out of 300 points in the EWCL parameter space scan which have negative sign, as shown in the following figure.

Works in progress

We are analyzing the current experiment constraint on the parameter space of EWCL, which will be useful for Tevatron II and LHC. Analysis of the constraint on parameter space and deriving the matching conditions with other models, like two Higgs doublet model, the extra dimension model, and little Higgs model, etc., is going on[6].

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