Low energy theorems for gauge boson scattering in left-right symmetric models

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Outline

QCD Lagrangian

Strong interactions are described by the QCD Lagrangian

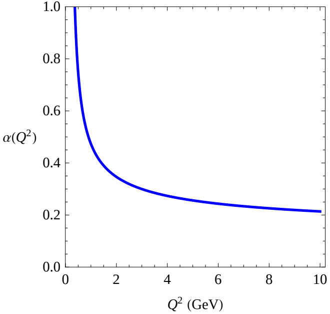
$$\mathcal{L}_{\rm QCD} = -\frac{1}{4} G^a_{\mu\nu} G^{a\mu\nu} + \bar{q}(i\gamma^\mu D_\mu - \mathcal{M})q$$

$$q = \mathrm{col}(u, d, s, c, b, t), \quad \mathcal{M} = \mathrm{diag}(m_u, m_d, m_s, m_c, m_b, m_t).$$

This theory have two important features

- Asymptotic Freedom at high energies
- Confinement at low energies

Scalar hadron states and the vacuum of QCD



$$\alpha(Q^2) = \frac{4\pi}{7\log\left(\frac{Q^2}{\lambda_{QCD}}\right)}$$

$$\lambda_{QCD} \approx 150\text{MeV}$$

- Hadron properties with $m < 2$ GeV cannot be described perturbatively
- How can we calculate?

Chiral Symmetry

For the light sector (u, d, s) in the massless limit, the QCD Lagrangian can be written as

$$\mathcal{L}^0_{\mathrm{QCD}} = -\frac{1}{4}G^a_{\mu\nu}G^{a\mu\nu} + \bar{q}_L(i\gamma^\mu D_\mu)q_L + \bar{q}_R(i\gamma^\mu D_\mu)q_R,$$

with

$$q_L = \tfrac{1}{2}(1-\gamma_5)q, \quad q_R = \tfrac{1}{2}(1+\gamma_5)q.$$

This Lagrangian is invariant under the action of

$$G_T = SU(3)_L \times SU(3)_R \times U(1)_{L+R}.$$

Chiral Perturbation Theory χPT

Chiral Perturbation Theory is the effective theory of the strong interactions at low energies ($\sqrt{s} < m_\rho$).

- Degrees of freedom $\rightarrow$ hadronic states
- Systematic expansion in $\frac{p^2}{\Lambda^2_{\chi PT}}$ and $\frac{m_q^2}{\Lambda^2_{\chi PT}}$
- It is based in the $SU(3)_L \times SU(3)_R \rightarrow SU(3)_{L+R}$ SSB
- 8 Goldstone bosons = 8 lightest pseudoscalar mesons

Chiral Lagrangian $\mathcal{O}(p^2)$

$$\mathcal{L}_2 = \frac{f^2}{4}\mathrm{Tr}\left\{(\partial_\mu U)^\dagger \partial^\mu U + 2B_0\left(U^\dagger + U\right)\mathcal{M}\right\}, \qquad U = e^{-\frac{i\sqrt{2}}{f}\Phi}$$

$$\Phi \equiv \frac{1}{\sqrt{2}}\sum_{a=1}^{8}\lambda^a\phi^a = \begin{pmatrix} \frac{1}{\sqrt{2}}\pi^0 + \frac{1}{\sqrt{6}}\eta_8 & \pi^+ & K^+ \\ \pi^- & -\frac{1}{\sqrt{2}}\pi^0 + \frac{1}{\sqrt{6}}\eta_8 & K^0 \\ K^- & \bar{K}^0 & -\frac{2}{\sqrt{6}}\eta_8 \end{pmatrix}.$$

Predictive Power of χPT

$\Lambda_{\chi PT} = 4\pi f \approx 1\text{GeV}$,

- $\mathcal{O}(p^2)$ Only 2 constants must be fixed: f (pion decay constant) and B_0 (related with the quark condensate)
- $\mathcal{O}(p^4)$ 12 parameters, needed to renormalize one loop $\mathcal{O}(p^2)$ calculations
- $\mathcal{O}(p^6)$ More than 100 parameters, predictive power is lost
- Existence of a light and wide scalar resonance σ: The chiral expansion is broken in the scalar sector!

Unitarized χPT

A successful description of meson-meson interactions up to $\sqrt{s} \approx$1.2 GeV can be achieved imposing unitary constraints in coupled channels. If the amplitude of a process is normalized according to

$$\frac{d\sigma}{d\Omega} = \frac{1}{64\pi^2 s} \frac{|\mathbf{k}_f|}{|\mathbf{k}_i|} |T_{if}|^2,$$

then, unitarity in coupled channels means

$$\mathrm{Im}\, T_{if} = \sum_j T_{ij}\, \sigma_{jj}\, T^*_{jf}\,,$$

$$\sigma_{jj}(s) = \mathrm{Im}\, G_j(s),$$

$$G_j(s) = i\mu^{2\varepsilon} \int \frac{d^d l}{(2\pi)^d} \frac{1}{l^2 - m^2_{1_j} + i\epsilon} \frac{1}{(l-P)^2 - m^2_{2_j} + i\epsilon},$$

In the case of s-wave meson-meson amplitudes, unitarization reduces to the solution of the Bethe-Salpeter equation

$$\mathbb{T} = \mathbb{T}_{(2)} + \mathbb{T}_{(2)} \cdot \mathbb{G} \cdot \mathbb{T}.$$

where $\mathbb{T}$ is the matrix of unitarized amplitudes of the desired Isospin channel, and $\mathbb{T}_{(2)}$ is the corresponding matrix of amplitudes calculated in χPT at $\mathcal{O}(p^2)$ factorized out of the loop integral with its on-shell values.[a].

[a] J. A. Oller, E. Oset and J. R. Pelaez, Phys. Rev. D **59**, 074001 (1999) [Erratum-ibid. D **60**, 099906 (1999)] [arXiv:hep-ph/9804209]

This unitarization process has the following advantages:

- Scalar resonances are generated dynamically as poles in the unitarized amplitude
- Involves only $\mathcal{O}(p^2)$ lagrangian
- Includes only one extra parameter: The cutoff of the momentum integral.

evaluation of $G_j(p^2)$

$$G_j(p^2) = \frac{1}{(4\pi)^2}\left\{-1 + \log\frac{m_j^2}{\mu^2} + \sigma(p^2)\log\frac{\sigma(p^2)+1}{\sigma(p^2)-1}\right\}.$$

$$\sigma(p^2) = \sqrt{1-\frac{4m_j^2}{p^2}} \qquad \mu = \frac{2\Lambda}{\sqrt{e}} \simeq 1.2\Lambda = 1.2\text{GeV}$$

Example

The pole contained in the unitarized s-wave isoscalar amplitude of $K\bar{K} \to \pi\pi$ can be identified with the scalar $f_0(980)$

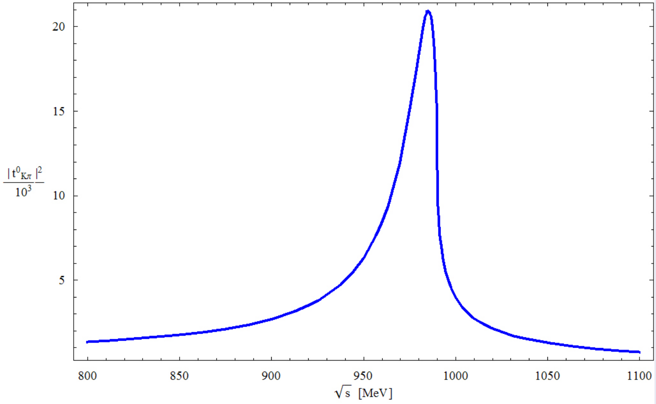


Figura: $|t^0_{K\pi}|^2$ around the mass of f_0

Origin of scalar states in Electroweak Theory

Despite the impressive success of the SM, we have made very little progress in understanding de origin of SSB. One major goal of the LHC is the better understanding of this phenomenon, and an essential feature of the problem is the analysis of gauge boson scattering $VV \to VV$.

The symmetry breaking sector can be of strong or weak nature, and the test energy scale is tipically $\mathcal{O}(1)$ TeV. Even though the dynamical mechanism underlying symmetry breakdown is not really understod, one can anticipate some features which should be present if scalar states are not elementary:

- The necessary existence of Goldstone bosons suggest the presence of strong forces
- There exists a natural scale for the Higgs sector, $v = \left(\sqrt{2}G_F\right)^{-1} \approx 250$ GeV
- if forces are of unit strength on this scale, masses on the order are to be expected $M_H \approx 1$TeV

Strong interacting scenario

If the Higgs mechanism turns to be realized, a Higgs boson is enough to restore unitarity in $VV \to VV$ reactions.
In models beyond SM the population of scalars increases dramatically, and if the SB sector turns out to be of strong nature, it is important to look carefully at the possible consequences. This can be achieved using a low energy description ef electroweak phenomena: an Effective theory.

Effective Electroweak Lagrangian $\mathcal{O}(p^2)$

The most general effective lagrangian compatible with global $SU(2)_L \times U(1)_Y$ is

$$\mathcal{L}_{EWSB} = \frac{v^2}{4}\mathrm{Tr}\left\{(\partial_\mu \Sigma)^\dagger \partial^\mu \Sigma\right\} + \frac{v^2}{8}\left(1 - \frac{1}{\rho}\right)\mathrm{Tr}\left\{\tau_3 \Sigma^\dagger \partial^\mu \Sigma\right\}^2,$$

$$\Sigma = e^{\frac{i\sqrt{2}}{v}\Phi} \qquad \Phi = \frac{1}{\sqrt{2}}\sum_{a=1}^{3}\tau_a \phi^a = \begin{pmatrix} \frac{1}{\sqrt{2}}\pi^0 & \pi^+ \\ \pi^- & -\frac{1}{\sqrt{2}}\pi^0 \end{pmatrix}.$$

Weak bosons

If the global symmetry is promoted to a local $SU(2)_L \times U(1)_Y$, the effective lagrangian for the gauge sector becomes

$$\mathcal{L}_{EWSB} = \frac{v^2}{4}\mathrm{Tr}\left\{(D_\mu\Sigma)^\dagger D^\mu\Sigma\right\} + \frac{v^2}{8}\left(1-\frac{1}{\rho}\right)\mathrm{Tr}\left\{\tau_3\Sigma^\dagger D^\mu\Sigma\right\}^2$$

$$\mathcal{L}_{Gauge} = -\frac{1}{2}\mathrm{Tr}\left\{\mathbf{W}^{\mu\nu}\mathbf{W}_{\mu\nu}\right\} - \frac{1}{2}\mathrm{Tr}\left\{\mathbf{B}^{\mu\nu}\mathbf{B}_{\mu\nu}\right\}$$

$$D_\mu\Sigma = \partial_\mu\Sigma + ig\mathbf{W}_\mu\Sigma - ig'\Sigma\mathbf{B}_\mu$$

$$\mathbf{W}_\mu = W^a_\mu\tau_a/2 \qquad \mathbf{W}_{\mu\nu} = \partial_\mu\mathbf{W}_\nu - \partial_\nu\mathbf{W}_\mu + ig\left[\mathbf{W}_\mu, \mathbf{W}_\nu\right]$$

$$\mathbf{B}_\mu = B_\mu\tau_3/2 \qquad \mathbf{B}_{\mu\nu} = \partial_\mu\mathbf{B}_\nu - \partial_\nu\mathbf{B}_\mu$$

Spontaneous Symmetry Breaking

In the Unitary gauge $\Sigma = 1$, the chiral lagrangian becomes

$$\mathcal{L}_{EWSB} = \frac{g^2 v^2}{4} W^+_\mu W^{-\mu} + \frac{g^2 v^2}{8\rho \cos^2\theta_w} Z_\mu Z^\mu$$

and we can read the vector boson masses

$$M_W = \frac{gv}{2} \qquad M_Z = \frac{gv}{2\rho\cos\theta_w}$$

Goldstone-boson Equivalence theorem

In the high-energy limit ($s, t, u \to \infty$) the scattering amplitudes of the longitudinal components of W and Z are equal as those of its absorbed Goldstones. This fact, known as the Equivalence Theorem (ET), enables us to approximate the contribution of longitudinally polarized gauge bosons to scattering amplitudes calculating only the scattering of the would-be Goldstone bosons. ET is valid in the energy domain $M_W^2 \ll s \ll \Lambda_{SB}^2$, where $\Lambda_{SB} = \text{mín}\{M_{SB}, 4\pi v\}$. ET is based on the fact that π^a fields in the effective lagrangian have the same quantum numbers as the divergence of the vector boson fields $\partial_\mu W^{a\mu}$. Depending on the gauge, there is a mixing term $\pi^a \partial_\mu W^{a\mu}$ and then a one-particle state $\pi^a |0\rangle$ has some overlap with the one-particle state $\partial_\mu W^{a\mu} |0\rangle$:

$$\langle 0| \pi^a \partial_\mu W^{a\mu} |0\rangle \neq 0$$

According with ET, two overlapping fields can be traded for each other in S-matrix calculations

$$\mathcal{M}\left[W(p_1),\ldots,W(p_n)\right]_U = \mathcal{M}\left[\pi(p_1),\ldots,\pi(p_n)\right]_R + \mathcal{O}\left(\frac{M}{E}\right)$$

in the energy domain where the expansion is valid.

low energy theorems

Equivalence theorem in action: Goldstone-boson scattering

- $\mathcal{M}\left(\pi^+\pi^- \to \pi^+\pi^-\right) = -\frac{u}{v^2}\left(4 - \frac{3}{\rho}\right)$
- $\mathcal{M}\left(\pi^+\pi^- \to \pi^0\pi^0\right) = \frac{s}{v^2\rho}$
- $\mathcal{M}\left(\pi^0\pi^0 \to \pi^0\pi^0\right) = 0$

Longitudinally polarized gauge vector scattering

- $\mathcal{M}\left(W_L^+W_L^- \to W_L^+W_L^-\right) = -\frac{u}{v^2}\left(4 - \frac{3}{\rho}\right) + \mathcal{O}(M_W^2/s)$
- $\mathcal{M}\left(W_L^+W_L^- \to Z_L^0Z_L^0\right) = \frac{s}{v^2\rho} + \mathcal{O}(M_W^2/s)$
- $\mathcal{M}\left(Z_L^0Z_L^0 \to Z_L^0Z_L^0\right) = 0 + \mathcal{O}(M_W^2/s)$

$$M_W^2 \ll s \ll \Lambda^2$$

$$\rho \approx 1.$$

Custodial Symmetry

In the limit $g' \to 0$ the Higgs sector of the SM has the global symmetry $SU(2)_L \times SU(2)_R$, The Higgs expectation value breaks the aproximate global symmetry in the pattern

$$SU(2)_L \times SU(2)_R \to SU(2)_{L+R}$$

This is equivalent to take $\rho = 1$ in the Chiral Lagrangian. In this approximation, Goldstones transform as a triplet under $SU(2)_{L+R}$ and LET's can be expressed in terms of a single function $A(s,t,u) = s/v^2$

- $\mathcal{M}\left(\pi^+\pi^- \to \pi^+\pi^-\right) = A(s,t,u) + A(t,u,s)$
- $\mathcal{M}\left(\pi^+\pi^- \to \pi^0\pi^0\right) = A(s,t,u)$
- $\mathcal{M}\left(\pi^0\pi^0 \to \pi^0\pi^0\right) = A(s,t,u) + A(t,u,s) + A(u,s,t)$

Unitarization of LET's

The s-wave isoscalar amplitude for Goldstone scattering $\pi\pi \to \pi\pi$ is

$$t_0 \equiv t^{(I=0)}_{(J=0)} = \frac{s}{v^2}.$$

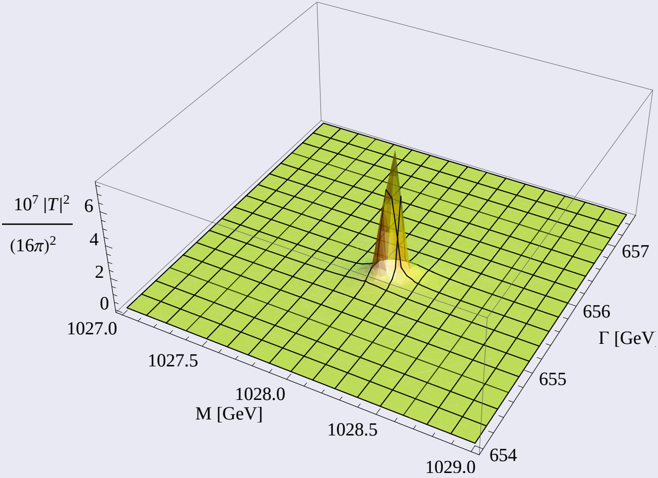
Expected energy scale where perturbation theory breaks down: $\Lambda_{E\chi PT} = 4\pi v \approx 3\text{TeV}$.

Bethe-Salpeter Equation

$$t = t_0 + t_0 G(p^2) t$$

$$G(p^2) = \frac{1}{(4\pi)^2}\left\{-1 + \log\frac{-p^2}{\mu^2}\right\} \qquad \mu \approx 3\text{TeV}$$

Pole position in the unitarized amplitude



Mass: $M_H \approx 1028$ GeV, Width: $\Gamma_H \approx 655$ GeV

Effective Chiral Lagrangian for *left-right* models

The bosonic sector of the most general Electroweak Chiral Lagrangian $\mathcal{O}(p^2)$ invariant under local $SU(2)_L \times SU(2)_R \times U(1)_{B-L}$ transformations is

$$\mathcal{L}_2 = -\frac{f_L^2}{4}\,\mathrm{Tr}\left\{X_{L\mu}X_L^{\mu}\right\} - \frac{f_R^2}{4}\,\mathrm{Tr}\left\{X_{R\mu}X_R^{\mu}\right\} + \frac{\kappa f_L f_R}{2}\,\mathrm{Tr}\left\{X_{L\mu}X_R^{\mu}\right\}$$
$$+\frac{\beta_L f_L^2}{8}\,\mathrm{Tr}\left\{\tau^3 X_L^{\mu}\right\}^2 + \frac{\beta_R f_R^2}{8}\,\mathrm{Tr}\left\{\tau^3 X_R^{\mu}\right\}^2 + \frac{\beta f_L f_R}{4}\,\mathrm{Tr}\left\{\tau^3 X_L^{\mu}\right\}\mathrm{Tr}\left\{\tau^3 X_R^{\mu}\right\}$$

$$\mathcal{L}_{\text{gauge}} = -\frac{1}{2}\,\mathrm{Tr}\left\{\mathcal{A}_{L\mu\nu}\mathcal{A}_L^{\mu\nu}\right\} - \frac{1}{2}\,\mathrm{Tr}\left\{\mathcal{A}_{R\mu\nu}\mathcal{A}_R^{\mu\nu}\right\} - \frac{1}{2}\,\mathrm{Tr}\left\{B'_{\mu\nu}B'^{\mu\nu}\right\}$$

$$X_A^{\mu} \equiv U_A^{\dagger}D^{\mu}U_A, \qquad D^{\mu}U_A = \partial^{\mu}U_A - ig\mathcal{A}_A^{\mu}U_A + ig'U_A B'^{\mu}.$$

$$\mathcal{A}_A^{\mu} = T^j A_A^{j\mu}, \qquad B' = T^3 B^{\mu}, \qquad U_A = e^{\frac{i\tau^j\pi_A^j}{f_A}},$$

$$T^j = \tau^j/2 \qquad j = 1, 2, 3 \qquad A = L, R.$$

Transformations

$$
\begin{aligned}
\mathcal{A}^{\mu}_{A} &\rightarrow -\frac{i}{g}\left[\partial^{\mu}\Omega_{A}\right]\Omega_{A}^{-1} + \Omega_{A}\mathcal{A}^{\mu}_{A}\Omega_{A}^{-1}, \\
B'^{\mu} &\rightarrow \frac{i}{g'}\Lambda\left[\partial^{\mu}\Lambda^{-1}\right] + B', \\
U_{A} &\rightarrow \Omega_{A}U_{A}\Lambda^{\dagger},
\end{aligned}
$$

with $\Omega_A(x) = e^{\frac{i}{2}\tau^j\theta^j_A(x)}$ and $\Lambda(x) = e^{\frac{i}{2}\tau^3\theta^0(x)}$.

Low energy constants

- f_L electroweak symmetry breaking scale: $f_L \approx 250$ GeV.
- f_R parity breaking scale
- κ, β_L, β_R & β: parameters for *left-right* mixing and explicit custodial symmetry breaking.

Parity breaking scale

If se set f_R of $\mathcal{O}(1)$ TeV, there is a sizable energy window of ET validity, described by $M^2 \ll s \ll \Lambda_{SB}^2$, with M as the mass of the heaviest gauge boson and $\Lambda_{SB} = \text{mín}\{M_{SB}, 4\pi f_L\}$.

SB breaking pattern

$$SU(2)_L \times SU(2)_R \times U(1)_{B-L} \to SU(2)_L \times U(1)_Y \to U(1)_{EM}$$

provided $f_L < f_R$.

Low Energy Theorems

Parameters f_L, f_R, κ, β_L, β_R and β of can be eliminated in favor of the masses and mixing angles of the gauge bosons: M_{W_1}, M_{W_2}, M_{Z_1}, M_{Z_2}, ξ and ϕ, and if no further assumption is made, θ_W is not constrained by them and becomes the seventh one. Definitive expressions for two-body scattering of the Nambu-Goldstone bosons in the energy range where the effective Lagrangian and the equivalence theorem are both valid, $M^2 \ll s \ll \Lambda_{SB}^2$ can be obtained from the $3-\pi$ and $4-\pi$ vertices

Using the following complementary definitions for further shortening of the expressions, 22 LET are obtained

$$
\begin{aligned}
A_0 &= \sqrt{\cos 2\theta}\sec^2\theta\sin 2\phi + \tan^2\theta\cos 2\phi, \\
B_0 &= \sqrt{\cos 2\theta}\sec^2\theta\cos 2\phi - \tan^2\theta\sin 2\phi \\
C_0 &= \cos 2\theta + \cos^2 2\xi, \\
F_1 &= \tan^2\theta\left(\cos^2 2\xi - \cos 2\theta\right) + 2\cos 2\theta\sec^2\theta\cos 2\xi, \\
F_2 &= \tan^2\theta\left(\cos^2 2\xi - \cos 2\theta\right) - 2\cos 2\theta\sec^2\theta\cos 2\xi, \\
G_1 &= 2\sqrt{\cos 2\theta}\sec^2\theta\sin^2\xi(\cos 2\theta + \cos 2\xi), \\
G_2 &= 2\sqrt{\cos 2\theta}\sec^2\theta\cos^2\xi(\cos 2\theta - \cos 2\xi).
\end{aligned}
$$

left-right low energy theorems

$$\mathcal{M}(w_1^+ w_1^- \to w_1^+ w_1^-) = -\frac{g^2 u}{16 M_{W_1}^4} \{ 8 M_{W_1}^2 (\cos 2\xi + 1) - 3 C_0 \left(M_{Z_1}^2 + M_{Z_2}^2 \right) + 3 \left(M_{Z_1}^2 - M_{Z_2}^2 \right) \left(G_1 \sin 2\phi - F_1 \cos 2\phi \right) \}$$

$$\mathcal{M}(w_2^+ w_2^- \to w_2^+ w_2^-) = -\frac{g^2 u}{16 M_{W_2}^4} \{ 8 M_{W_2}^2 (\cos 2\xi + 1) - 3 C_0 \left(M_{Z_1}^2 + M_{Z_2}^2 \right) + 3 \left(M_{Z_1}^2 - M_{Z_2}^2 \right) \left(G_2 \sin 2\phi - F_2 \cos 2\phi \right) \}$$

$$\mathcal{M}(w_1^+ w_2^- \to w_1^+ w_1^-) = -\frac{g^2 u \sin 2\xi}{16 M_{W_1}^3 M_{W_2}} \Big\{ \cos 2\xi \left[6M_{W_1}^2 + 2M_{W_2}^2 - 3\left(M_{Z_1}^2 + M_{Z_2}^2\right)\right] - 3\left(M_{Z_1}^2 - M_{Z_2}^2\right)\left(A_0 \cos 2\xi + B_0 \sqrt{\cos 2\theta}\right)\Big\}$$

$$\mathcal{M}(w_1^+ w_2^- \to w_2^+ w_2^-) = \frac{g^2 u \sin 2\xi}{16 M_{W_1} M_{W_2}^3} \Big\{ \cos 2\xi \left[6M_{W_2}^2 + 2M_{W_1}^2 - 3\left(M_{Z_1}^2 + M_{Z_2}^2\right)\right] - 3\left(M_{Z_1}^2 - M_{Z_2}^2\right)\left(A_0 \cos 2\xi - B_0 \sqrt{\cos 2\theta}\right)\Big\}$$

$$\mathcal{M}(w_2^+ w_1^- \to w_1^+ w_1^-) = \mathcal{M}(w_1^+ w_2^- \to w_1^+ w_1^-)$$

$$\mathcal{M}(w_2^+ w_2^- \to w_2^+ w_1^-) = \mathcal{M}(w_2^+ w_2^- \to w_1^+ w_2^-)$$

$$\mathcal{M}(w_1^+ w_2^- \to w_1^+ w_2^-) =$$
$$- \frac{g^2}{16 M_{W_1}^2 M_{W_2}^2 M_{Z_1}^2 M_{Z_2}^2} \Big\{ \sin^2 2\xi \Big\{ s \left(M_{W_1}^2 - M_{W_2}^2\right)^2 \left(M_{Z_1}^2 + M_{Z_2}^2\right)$$
$$+ A_0 \left(M_{Z_2}^2 - M_{Z_1}^2\right) \left[s \left(M_{W_1}^2 - M_{W_2}^2\right)^2 + 3 M_{Z_1}^2 M_{Z_2}^2 u \right]$$
$$+ M_{Z_1}^2 M_{Z_2}^2 u \left[4 \left(M_{W_1}^2 + M_{W_2}^2\right) - 3 \left(M_{Z_1}^2 + M_{Z_2}^2\right)\right] \Big\}$$
$$+ 2 M_{Z_1}^2 M_{Z_2}^2 (u - s) \left[A_0 \left(M_{Z_1}^2 - M_{Z_2}^2\right) \cos^2\theta + \left(M_{Z_1}^2 + M_{Z_2}^2\right) \sin^2\theta \right] \Big\}$$

$$\mathcal{M}(w_1^+ w_2^- \to w_2^+ w_1^-) = \mathcal{M}(w_1^+ w_2^- \to w_1^+ w_2^-)|_{s=u}$$

$$\mathcal{M}(w_2^+ w_1^- \to w_2^+ w_1^-) = \mathcal{M}(w_1^+ w_2^- \to w_1^+ w_2^-)$$

$$\mathcal{M}(w_1^+ w_1^- \to z_1 z_1) = \frac{g^2 s}{16 M_{W_1}^4 M_{W_2}^2 M_{Z_1}^2} \Big\{ M_{W_2}^2 M_{Z_1}^4 (C_0 + F_1 \cos 2\phi - G_1 \sin 2\phi) + (1 + A_0) \sin^2 2\xi M_{W_1}^2 \left[\left(M_{W_1}^2 + M_{W_2}^2 - M_{Z_1}^2 \right)^2 - 4 M_{W_2}^2 \left(M_{W_2}^2 - M_{Z_1}^2 \right) \right] \Big\}$$

$$\mathcal{M}(w_1^+ w_1^- \to z_2 z_2) = \frac{g^2 s}{16 M_{W_1}^4 M_{W_2}^2 M_{Z_2}^2} \Big\{ M_{W_2}^2 M_{Z_2}^4 (C_0 - F_1 \cos 2\phi + G_1 \sin 2\phi) + (1 - A_0) \sin^2 2\xi M_{W_1}^2 \left[\left(M_{W_1}^2 + M_{W_2}^2 - M_{Z_2}^2 \right)^2 - 4 M_{W_2}^2 \left(M_{W_2}^2 - M_{Z_2}^2 \right) \right] \Big\}$$

$$\mathcal{M}(w_2^+ w_2^- \to z_2 z_2) = \frac{g^2 s}{16 M_{W_1}^2 M_{W_2}^4 M_{Z_2}^2} \Big\{ M_{W_1}^2 M_{Z_2}^4 (C_0 - F_2 \cos 2\phi + G_2 \sin 2\phi) + (1 - A_0) \sin^2 2\xi M_{W_2}^2 \Big[\left(M_{W_1}^2 + M_{W_2}^2 - M_{Z_2}^2 \right)^2 - 4 M_{W_1}^2 \left(M_{W_1}^2 - M_{Z_2}^2 \right) \Big] \Big\}$$

$$\mathcal{M}(w_2^+ w_2^- \to z_1 z_1) = \frac{g^2 s}{16 M_{W_1}^2 M_{W_2}^4 M_{Z_1}^2} \Big\{ M_{W_1}^2 M_{Z_1}^4 (C_0 + F_2 \cos 2\phi - G_2 \sin 2\phi) + (1 + A_0) M_{W_2}^2 \sin^2 2\xi \Big[\left(M_{W_1}^2 + M_{W_2}^2 - M_{Z_1}^2 \right)^2 - 4 M_{W_1}^2 \left(M_{W_1}^2 - M_{Z_1}^2 \right) \Big] \Big\}$$

$$\mathcal{M}(w_1^+ w_1^- \to z_1 z_2) = \frac{g^2 s}{16 M_{W_1}^4 M_{W_2}^2 M_{Z_1} M_{Z_2}} \Big\{ M_{W_2}^2 M_{Z_1}^2 M_{Z_2}^2 (F_1 \sin 2\phi + G_1 \cos 2\phi) + B_0 \sin^2 2\xi M_{W_1}^2 \left[\left(M_{W_2}^2 - M_{W_1}^2 \right) \left(M_{W_1}^2 + 3 M_{W_2}^2 - M_{Z_1}^2 - M_{Z_2}^2 \right) - M_{Z_1}^2 M_{Z_2}^2 \right] \Big\}$$

$$\mathcal{M}(w_2^+ w_2^- \to z_1 z_2) = \frac{g^2 s}{16 M_{W_1}^2 M_{W_2}^4 M_{Z_1} M_{Z_2}} \Big\{ M_{W_1}^2 M_{Z_1}^2 M_{Z_2}^2 (F_2 \sin 2\phi + G_2 \cos 2\phi) + B_0 \sin^2 2\xi M_{W_2}^2 \left[\left(M_{W_1}^2 - M_{W_2}^2 \right) \left(3 M_{W_1}^2 + M_{W_2}^2 - M_{Z_1}^2 - M_{Z_2}^2 \right) - M_{Z_1}^2 M_{Z_2}^2 \right] \Big\}$$

$$\mathcal{M}(w_2^+ w_1^- \to z_1 z_1) = -\frac{g^2 s \sin 2\xi}{16 M_{W_1}^3 M_{W_2}^3 M_{Z_1}^2}\left\{B_0\sqrt{\cos 2\theta} M_{Z_1}^2 \left[\left(M_{W_1}^2 - M_{W_2}^2\right)^2 - M_{Z_1}^2\left(M_{W_1}^2 + M_{W_2}^2\right)\right] + (1 + A_0)\cos 2\xi \left(M_{W_1}^2 - M_{W_2}^2\right)\left[M_{Z_1}^2\left(M_{Z_1}^2 - M_{W_1}^2 - M_{W_2}^2\right) + 4 M_{W_1}^2 M_{W_2}^2\right]\right\}$$

$$\mathcal{M}(w_2^+ w_1^- \to z_2 z_2) = \frac{g^2 s \sin 2\xi}{16 M_{W_1}^3 M_{W_2}^3 M_{Z_2}^2}\left\{B_0\sqrt{\cos 2\theta} M_{Z_2}^2 \left[\left(M_{W_1}^2 - M_{W_2}^2\right)^2 - M_{Z_2}^2\left(M_{W_1}^2 + M_{W_2}^2\right)\right] + (1 - A_0)\cos 2\xi \left(M_{W_2}^2 - M_{W_1}^2\right)\left[M_{Z_2}^2\left(M_{Z_2}^2 - M_{W_1}^2 - M_{W_2}^2\right) + 4 M_{W_1}^2 M_{W_2}^2\right]\right\}$$

$$\mathcal{M}(w_1^+ w_2^- \to z_1 z_1) = \mathcal{M}(w_2^+ w_1^- \to z_1 z_1)$$

$$\mathcal{M}(w_1^+ w_2^- \to z_2 z_2) = \mathcal{M}(w_2^+ w_1^- \to z_2 z_2)$$

$$\mathcal{M}(w_2^+ w_1^- \rightarrow z_1 z_2) =$$

$$\frac{g^2 \sin 2\xi}{16 M_{W_1}^3 M_{W_2}^3 M_{Z_1} M_{Z_2}} \Big\{ B_0 \cos 2\xi \left(M_{W_1}^2 - M_{W_2}^2\right) \left[s\left(4 M_{W_1}^2 M_{W_2}^2 + M_{Z_1}^2 M_{Z_2}^2\right) \right.$$

$$\left. + M_{W_1}^2 \left(M_{Z_1}^2 t + M_{Z_2}^2 u\right) + M_{W_2}^2 \left(M_{Z_1}^2 u + M_{Z_2}^2 t\right)\right] + \sqrt{\cos 2\theta} \left(M_{W_2}^2 - M_{W_1}^2\right)$$

$$\left[M_{W_1}^2 \left(M_{Z_1}^2 t - M_{Z_2}^2 u\right) + M_{W_2}^2 \left(M_{Z_2}^2 t - M_{Z_1}^2 u\right) + M_{Z_1}^2 M_{Z_2}^2 (u - t)\right]$$

$$+ A_0 \sqrt{\cos(2\theta)} \big\{ M_{W_1}^4 \left(M_{Z_1}^2 t + M_{Z_2}^2 u\right) + M_{W_2}^4 \left(M_{Z_1}^2 u + M_{Z_2}^2 t\right)$$

$$+ s \left[M_{W_1}^2 M_{W_2}^2 \left(M_{Z_1}^2 + M_{Z_2}^2\right) + M_{Z_1}^2 M_{Z_2}^2 \left(M_{W_1}^2 + M_{W_2}^2\right)\right] \big\} \Big\}$$

$$\mathcal{M}(w_1^+ w_2^- \rightarrow z_1 z_2) = \mathcal{M}(w_2^+ w_1^- \rightarrow z_1 z_2)|_{u \leftrightarrow t}$$

$$\mathcal{M}(z_i z_j \rightarrow z_k z_l) = 0 \qquad (i, j, k, l = 1, 2).$$

Conclusions and perspectives

- If the SB sector is of strong nature in the $SU(2)_L \times U(1)_Y$ context, the lightest scalar state can be generated dynamically following a simple unitarization procedure
- This scalar state has a mass $M_H \approx 1$TeV and turns to be very wide $\Gamma_H \approx$0.65TeV.
- This non-elementary Higgs state is analogous to the σ scalar meson
- If the parity breaking energy scale is $\mathcal{O}(1)$TeV, there exist the possibility of observing strong dynamics in a $SU(2)_L \times SU(1)_R \times U(1)_{B-L}$ framework.
- In such case, the low energy theorems derived in this work are valid for all left-right symmetric models.

Thanks