

Phenomenology at the LHC of composite particles from strongly interacting Standard Model fermions via four-fermion operators of NJL type

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in collaboration with

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here dedicate to Professor Giuliano Preparata

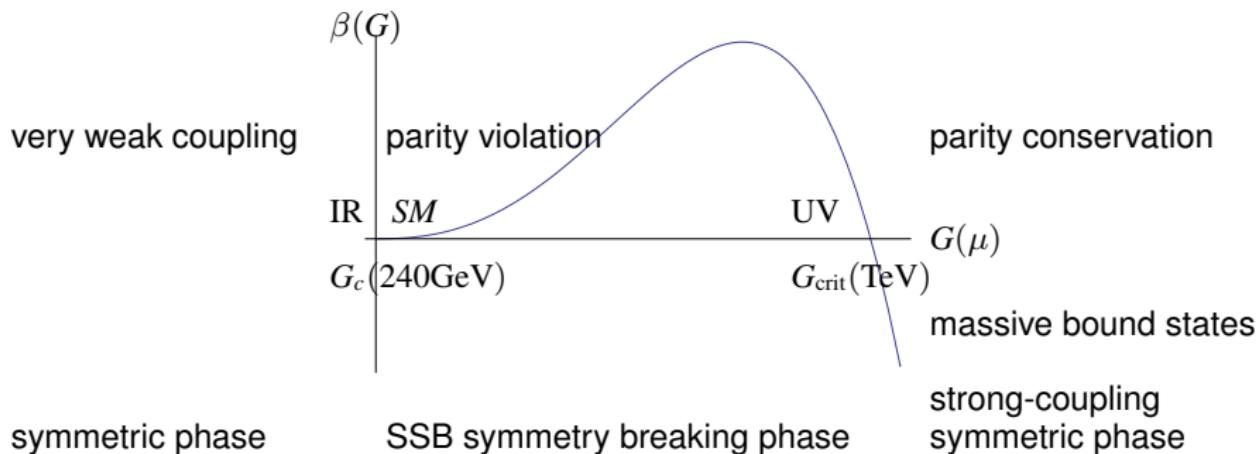
Outline of theoretical part: four-fermion operators, second-order phase transitions, IR- and UV-fixed points and domains.

1. Effective four-fermion operators originated by some unknown dynamics, for example the quantum gravity provides the SM field theory a neutral regulator at the basic space-time cutoff Λ .
2. The phase transitions of gauge symmetric and symmetry-breaking phases occur at the critical points of both weak and strong four-fermion couplings. In the domains (scaling regions) of IR- and UV-stable fixed points (critical points) of the four-fermion coupling, effective gauge field theories are achieved with the characteristic energy scales.
3. The weak-coupling IR-domain associates to the SSB dynamics and SM physics at $\mathcal{E} \sim 240$ GeV. The strong coupling UV-domain associates to the bound-state dynamics and new physics at $\mathcal{E} \sim$ TeV.

- S.-S. Xue, PLB381 (1996) 277; NPB486 (1997) 282, B580 (2000) 365; . . .; PLB737 (2014) 172; PRD93, 073001 (2016); JHEP 11 (2016) 072; JHEP 05(2017)146.

Outline: β -function sketch of four-fermion coupling G . UV-fixed point and domain of TeV.

$$\mathcal{L} = i\bar{\psi}_{L,R}\partial\psi_{L,R} - G(\bar{\psi}_L\psi_R)(\bar{\psi}_R\psi_L)$$



- Y. Nambu and G. Jona-Lasinio, Phys. Rev. 122 (1961) 345.
- W. A. Bardeen, C. T. Hill and M. Lindner, PRD (1990) 1647.

This is reminiscent of the QCD dynamics: asymptotically free quark states in the domain of a UV-stable fixed point and bound hadron states in the domain of a possible IR-stable fixed point.

Relevant four-fermion operators in the IR-domain.

SSB responsible for top-quark, composite Higgs, W^\pm and Z^0 masses.

In the quark sector,

$$G \left[(\bar{\psi}_L^{ia} t_{Ra}) (\bar{t}_R^b \psi_{Lib}) + (\bar{\psi}_L^{ia} b_{Ra}) (\bar{b}_R^b \psi_{Lib}) \right] + \dots, \quad (1)$$

the $SU_L(2)$ doublet $\psi_L^{ia} = (t_L^a, b_L^a)$ and singlet $\psi_R^a = t_R^a, b_R^a$. As an energetically favorable solution of the SSB ground state, only top-quark is massive, otherwise there would be more Goldstone modes. The effective four-fermion coupling in the lepton sector is N_c -time smaller than that in the quark sector. As a result, among four-fermion operators, the $(\bar{t}_L t_R)(\bar{t}_R t_L)$ is the unique relevant one undergoing the SSB, the effective Lagrangian in the IR-domain

$$\begin{aligned} L &= L_{\text{kinetic}} + g_{t0}(\bar{\Psi}_L t_R H + \text{h.c.}) + \Delta L_{\text{gauge}} \\ &+ Z_H |D_\mu H|^2 - m_H^2 H^\dagger H - \frac{\lambda_0}{2} (H^\dagger H)^2. \end{aligned}$$

- W. A. Bardeen, C. T. Hill and M. Lindner, PRD (1990) 1647.
- G. Preparata and S.-S. Xue, PLB264 (1991) 35; ... PLB377 (1996) 124.

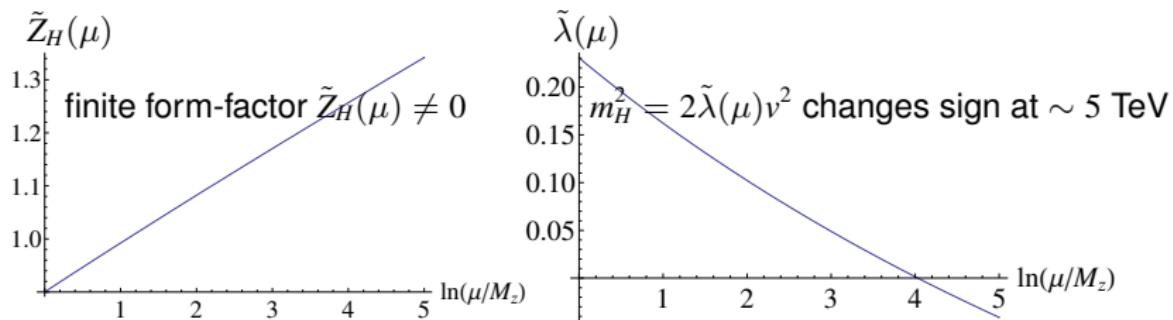
Relevant four-fermion operators in the IR-domain.

SSB responsible for top-quark, composite Higgs, W^\pm and Z^0 masses.

In the IR-domain of the energy scale $v = 239.5$ GeV, solve RG equations for the form factor \tilde{Z}_H and quartic coupling $\tilde{\lambda}(\mu^2)$ and mass-shell conditions

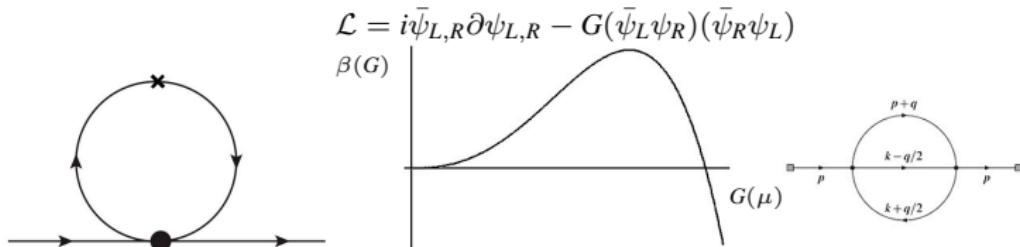
$$m_t(m_t) = \bar{g}_t^2(m_t)v/\sqrt{2} \approx 173\text{GeV}, \quad m_H(m_H) = [2\tilde{\lambda}(m_H)]^{1/2}v \approx 126\text{GeV}.$$

to obtain unique solutions $\tilde{Z}_H(\mu)$ and $\tilde{\lambda}(\mu)$



indicating the composite Higgs particle behaves an elementary particle, then binds with an elementary fermion ψ to a massive composite fermions $\Psi \sim (H\psi)$ in the gauge symmetric phase at the critical point of the 2nd phase transition around ~ 5 TeV.

The UV-stable fixed point for an effective field theory of massive composite particles at TeV.



SM-gauge symmetric (vector-like) composite particle spectra and interacting vertexes in the UV-domain of TeV scale. For the u -quark channel, the massive composite boson is an $SU_L(2)$ -doublet

$$\mathcal{A}^i = [Z_{\Pi}^S]^{-1/2} (\bar{u}_{Ra} \psi_L^{ia}), \quad M_{\Pi}^2 \mathcal{A}^i \mathcal{A}^{i\dagger}, \quad (2)$$

which combines with another quark to form the composite Weyl-fermion states,

$$\Psi_R^{ib} = (Z_R^S)^{-1} \mathcal{A}^i u_R^b; \quad \Psi_L^b = (Z_L^S)^{-1} \mathcal{A}^{i\dagger} \psi_{iL}^b, \quad (3)$$

and the massive composite Dirac fermions: $SU_L(2)$ doublet Ψ_D^{ib} and singlet Ψ_D^b ,

$$\Psi_D^{ib} = (\psi_L^{ib}, \Psi_R^{ib}), \quad \Psi_D^b = (\Psi_L^b, u_R^b), \quad M_F \bar{\Psi}_D^{ib} \Psi_D^{ib}, \quad \text{and} \quad M_F \bar{\Psi}_D^b \Psi_D^b. \quad (4)$$

where the form-factors $Z_{R,L}^S$ and $[Z_{\Pi}^S]^{1/2}$ are generalized wave-function renormalization of composite fermion and boson operators.

SM gauge symmetric four-fermion operators and quark-lepton interactions

In terms of the eigenstates of electroweak interactions, $SU_L(2)$ doublet $\psi_L^{ia} = (t_L^a, b_L^a)$ and singlet $\psi_R^a = t_R^a, b_R^a$, the four-fermion operators in the quark sector are

$$G \left[(\bar{\psi}_L^{ia} t_{Ra}) (\bar{t}_R^b \psi_{Lib}) + (\bar{\psi}_L^{ia} b_{Ra}) (\bar{b}_R^b \psi_{Lib}) \right] + \dots$$

In the lepton sector,

$$G \left[(\bar{\ell}_L^i \ell_R) (\bar{\ell}_R \ell_L) + (\bar{\ell}_L^\ell \nu_R^\ell) (\bar{\nu}_R^\ell \ell_L) + (\bar{\nu}_R^{\ell c} \nu_R^\ell) (\bar{\nu}_R^\ell \nu_R^{\ell c}) \right],$$

lepton $SU_L(2)$ doublets $\ell_L^i = (\nu_L^\ell, \ell_L)$, singlets ℓ_R and the conjugate fields of sterile neutrinos $\nu_R^{\ell c} = i\gamma_2(\nu_R^\ell)^*$,

$$G \left[(\bar{\nu}_R^{\ell c} \ell_R) (\bar{\ell}_R \nu_R^{\ell c}) + (\bar{\nu}_R^{\ell c} u_{a,R}^\ell) (\bar{u}_{a,R}^\ell \nu_R^{\ell c}) + (\bar{\nu}_R^{\ell c} d_{a,R}^\ell) (\bar{d}_{a,R}^\ell \nu_R^{\ell c}) \right],$$

where quark fields $u_{a,R}^\ell = (u, c, t)_{a,R}$ and $d_{a,R}^\ell = (d, s, b)_{a,R}$, and four-fermion operators of quark-lepton interactions ($\psi_{Lia} = (u_{La}, d_{La})$),

$$G \left[(\bar{\ell}_L^i e_R) (\bar{d}_R^a \psi_{Lia}) + (\bar{\ell}_L^i \nu_R^e) (\bar{u}_R^a \psi_{Lia}) \right] + \dots,$$

in the framework of the $SU(5)$ or $SO(10)$ unification theory.

- E. Eichten, J. Preskill, NPB 268 (1986) 179;

- M. Creutz, C. Rebbi, M. Tytgat, S.-S. Xue, PLB 402 (1997) 341; S.-S. Xue, MPLA, 14 (1999) 2701.

Composite particles and contact interactions

Operator	Composite fermion F_R	Composite fermion \bar{F}_L	Composite boson Π
$(\bar{\nu}_L^e e_R)(\bar{d}_R^a u_{La})$	$E_R^0 \sim e_R(\bar{d}_R^a u_{La})$	$\bar{E}_L^0 \sim \bar{e}_L(\bar{u}_R^a d_{La})$	$\Pi^+ \sim (\bar{d}_R^a u_{La})$
$(\bar{e}_L \nu_R^e)(\bar{u}_R^a d_{La})$	$N_R^- \sim \nu_R^e(\bar{u}_R^a d_{La})$	$\bar{N}_L^+ \sim \bar{\nu}_L^e(\bar{d}_R^a u_{La})$	$\Pi^- \sim (\bar{u}_R^a d_{La})$
$(\bar{e}_L e_R)(\bar{d}_R^a d_{La})$	$E_R^- \sim e_R(\bar{d}_R^a d_{La})$	$\bar{E}_L^+ \sim \bar{e}_L(\bar{d}_L^a d_{Ra})$	$\Pi_d^0 \sim (\bar{d}_R^a d_{La})$
$(\bar{\nu}_L^e \nu_R^e)(\bar{u}_R^a u_{La})$	$N_R^0 \sim \nu_R^e(\bar{u}_R^a u_{La})$	$\bar{N}_L^0 \sim \bar{\nu}_L^e(\bar{u}_L^a u_{Ra})$	$\Pi_u^0 \sim (\bar{u}_R^a u_{La})$

Table: Four-fermion operators and possible composite fermions F and composite bosons Π . The color a index is summed.

