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

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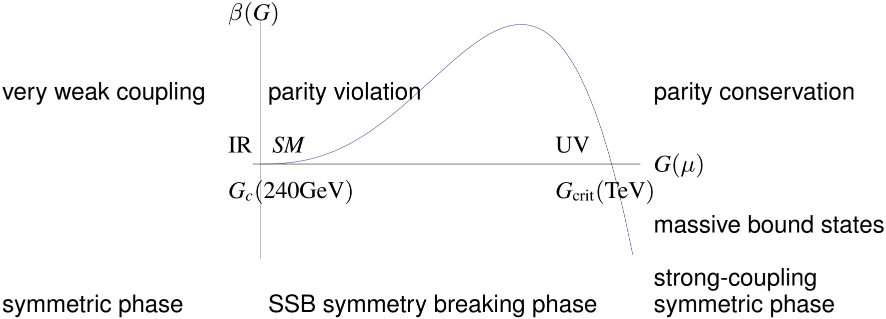
Outline of theoretical part: Physically compelling reasons for four-fermion operators, IR- and UV-fixed points, composite states of SM particles.

For the reason (No-Go theorem) that the SM bilinear Lagrangian $\bar{\psi}\hat{O}\psi$ in fermion fields is inconsistent in a UV cutoff field theory, effective four-fermion operators of Nambu-Jona-Lasinio type $-G(\bar{\psi}_L\psi_R)(\bar{\psi}_R\psi_L)$ must be originated by some unknown dynamics at the cutoff Λ.



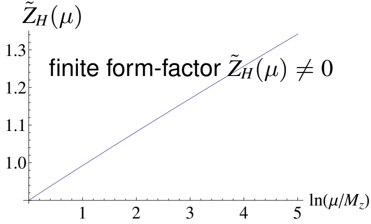
- No-Go theorem: H.B. Nielsen and M. Ninomiya, Nucl. Phys. B 185 (1981) 20 and B 193 (1981) 173;
- G. Preparata and S.-S. Xue, PLB264(1991)35; S.-S. Xue, PLB381(1996)277; NPB486 (1997) 282, B580 (2000) 365,· · ·.

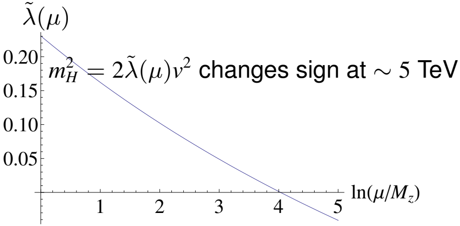
IR-domain: SSB for top-quark, composite Higgs, $W^{\pm}$ and Z^0 masses.

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 $\bar{\lambda}(\mu^2)$ 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 $\tilde{\lambda}(\mu)$ Y. Nambu and G. Jona-Lasinio, Phys. Rev. 122 (1961) 345, W. A. Bardeen, C. T. Hill and M. Lindner, PRD (1990) 1647; S.-S. Xue, PLB727 (2013) 308, B737 (2014) 172.





indicating the composite Higgs particle behaves an elementary particle, then binds with an elementary fermion ψ to a massive composite fermions $\Psi \sim (H\psi)$ around $\gtrsim 5$ TeV.

UV domain: an effective field theory of massive composite particles at TeV.

Composite fermions and bosons can be

- $F^f_R \sim \psi^f_R(\bar\psi^f_R \psi^f_L)$ (bound states of three SM fermions) with effective coupling $(\mathrm{g}_*/\Lambda)^2 \bar\psi^f_L(\bar\psi^f_L \psi^f_R) F^f_R \ + \ \mathrm{h.c.}$
- $\Pi^f \sim (\bar\psi^f_R \psi^f_L)$ (bound states of two SM fermions) with effective coupling $(\mathrm{F}_\Pi/\Lambda)^2 (\bar\psi^f_L \psi^f_R) \Pi^f \ + \ \mathrm{h.c.}$

  Λ = composite scale = O(TeV), $g_*/\Lambda^2 = 4\pi/\Lambda^2$ = a geometric cross section in the order of magnitude of inelastic processes forming composite fermions
  $(F_\Pi/\Lambda)^2$ = Yukawa coupling between composite boson and two fermionic constituents
  For a given Λ, the effective theory of composite particles is fully characterized in terms of the coupling F_Π, and the masses m_F and m_Π

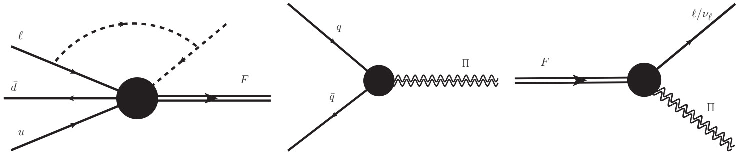
Operator	Composite fermion F_R	Composite fermion $\bar F_L$	Composite boson Π
$(\bar\nu^e_L e_R)(\bar d^a_R u_{La})$	$E^0_R \sim e_R(\bar d^a_R u_{La})$	$\bar E^0_L \sim \bar e_L(\bar u^a_R d_{La})$	$\Pi^+ \sim (\bar d^a_R u_{La})$
$(\bar e_L \nu^e_R)(\bar u^a_R d_{La})$	$N^-_R \sim \nu^e_R(\bar u^a_R d_{La})$	$\bar N^+_L \sim \bar\nu^e_L(\bar d^a_R u_{La})$	$\Pi^- \sim (\bar u^a_R d_{La})$
$(\bar e_L e_R)(\bar d^a_R d_{La})$	$E^-_R \sim e_R(\bar d^a_R d_{La})$	$\bar E^+_L \sim \bar e_L(\bar d^a_L d_{Ra})$	$\Pi^0_d \sim (\bar d^a_R d_{La})$
$(\bar\nu^e_L \nu^e_R)(\bar u^a_R u_{La})$	$N^0_R \sim \nu^e_R(\bar u^a_R u_{La})$	$\bar N^0_L \sim \bar\nu^e_L(\bar u^a_L u_{Ra})$	$\Pi^0_u \sim (\bar u^a_R u_{La})$

E. Eichten, J. Preskill, NPB268 (1986) 179; M. Creutz, C. Rebbi, M. Tytgat, S.-S. Xue, PLB 402(1997)341;

S.-S. Xue, the references in the first page, and PRD93, 073001 (2016); JHEP 11(2016)072; JHEP 05(2017)146

LHC phenomenology of composite particles at TeV scale

- The Feynman diagram representations for the composite fermions F and boson Π are



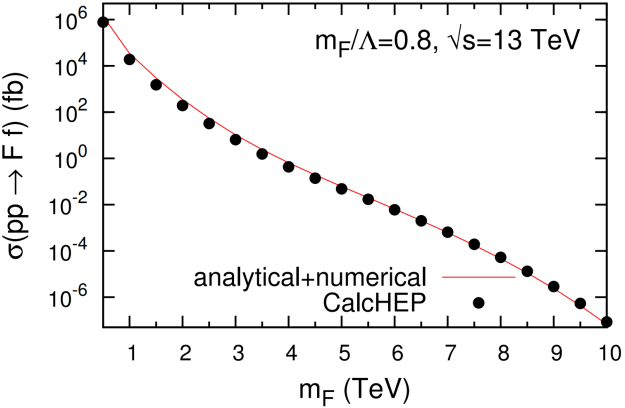
- Today, we describe the phenomenology at the LHC considering the most left diagram.
- By a crossing symmetry applied to the fermion line $f \to f^\dagger$ (dashed line) the same diagram describes a $2 \to 2$ production process:

$$q\bar{q} \to fF$$

f is a SM fermion

F is a composite fermion, whose flavour correspond to the SM flavour of f

Production cross-section for the process $pp \to fF$



Good agreement between analytical+numerical calculation and the results of the CalcHEP simulation, which validates the model implementation

Decay of the composite fermion F and decay chain of $pp \to fF$

Decay of the comopsite fermion F through 2 different channels

- $F \to \bar{f}\, qq'$
- $F \ \to \bar{f}\ \Pi^{0,\pm}$

Full decay chain is

- pp $\to fF \to f\bar{f}qq'$
- pp $\to fF \to f\bar{f}\ \Pi^{0,\pm}$

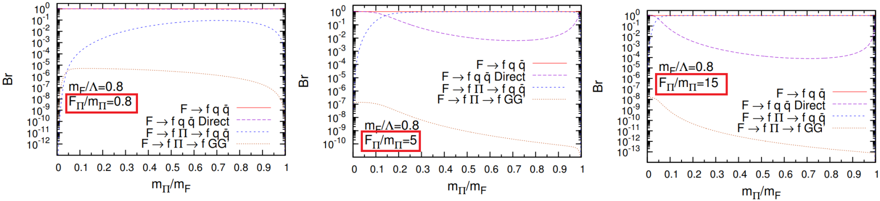
Note that

- if Π = Π^{+} or Π^{-} $\to$, only $\Pi \to qq'$ is allow
- if Π = Π^{0}, $\Pi \to \tilde{G}\tilde{G}'$ ($G = \gamma, Z, W$) is also possible. This case turns out to be negligible (see below).

Remember: for a given Λ, the effective theory of composite particles is fully characterized in terms of the coupling F_{Π}, and the masses m_F and m_{Π}

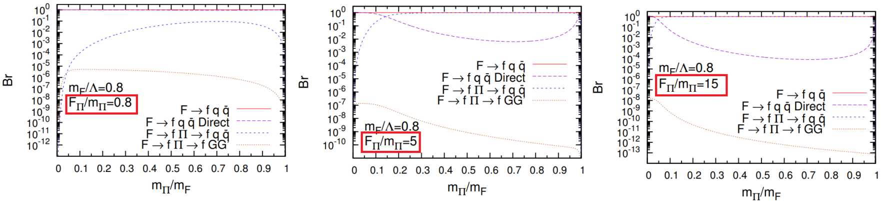
- $m_F/\Lambda < 1$ ($m_{\Pi}/\Lambda < 1$): insight into the dynamics of composite fermion (boson) formation
- F_{Π}/m_{Π}: m_{Π} and F_{Π} represent the same dynamics of composite boson formation
- $m_{\Pi}/m_F < 1$: to take into account F as composed by a composite boson and an elementary SM fermion

Decay branching ratio of F



- $F \to f\Pi \to fG\tilde{G}'$ always negligible
- $\Pi^0 \to \tilde{G}\tilde{G}'$ is the only case to depend from $m_F/\Lambda < 1$, which means the decay of F is fully characterized by the 2 parameters F_Π/m_Π and $m_\Pi/m_F < 1$
- the Br($F \to fq\bar{q}$ direct) and Br($F \to f\Pi \to fq\bar{q}$ indirect) tend to swap each other for different values of F_Π/m_Π this is important in terms of the signal topology, as it determines whether an intermediate resonance is produced

Relevant channels for the process $pp \to fF$ at the LHC



F_Π/m_Π	m_Π/m_F	Channel	Resonances	Topology	Experimental features
15	$[\sim 0.2, \sim 1]$	$fF \to f(\bar{f}\Pi) \to f(\bar{f}(qq'))$	F, Π	Resolved w/ $\Pi \to qq'$	identification of Π and F
	≤ 0.2	$fF \to f(\bar{f}\Pi) \to f(\bar{f}(qq'))$	F, Π	Boosted	identification of F; Π large-radius jet: 2-prong, no V boson tag
≤ 0.8	[0,1]	$fF \to f(\bar{f}qq')$	F	Fully resolved	same of $F_\Pi/m_\Pi = 10$

Same consideration applies to values of F_Π/m_Π between 0.8 and 15

Relevant signatures for investigating the process $pp \to fF$ at the LHC

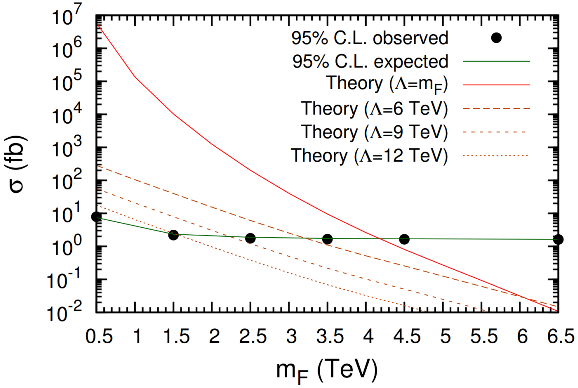
f = SM fermion; F = composite fermion, whose flavour correspond to the SM flavour of f
F particles not necessarily mass degenerate $\to$ each flavour searched for separately

f	F	Topology	Final state	LHC searches	Features not exploited in LHC searches
e	E	Fully resolved	$e^\pm(e^\mp qq')$	[28, 48]	E identification
		Resolved w/ $\Pi \to qq'$	$e^\pm(e^\mp(qq'))$	[48, 52]	E, Π identification
		Boosted	$e^\pm e^\mp J$	[28]	2-prong, no V boson tag, boosted Π decay
μ	M	Fully resolved	$\mu^\pm(\mu^\mp qq')$	[28, 48]	M identification
		Resolved w/ $\Pi \to qq'$	$\mu^\pm(\mu^\mp(qq'))$	[48, 52]	M, Π identification
		Boosted	$\mu^\pm\mu^\mp J$	[28]	2-prong, no V boson tag, boosted Π decay
τ	$\mathcal{T}$	Fully resolved	$\tau^\pm(\tau^\mp qq')$	[49]	$\mathcal{T}$ identification
		Resolved w/ $\Pi \to qq'$	$\tau^\pm(\tau^\mp(qq'))$	[49]	$\mathcal{T}, \Pi$ identification
		Boosted	$\tau^\pm\tau^\mp J$	n/a	
ν	N	Fully resolved	$\nu(\nu qq')$	[50, 51]	N identification
		Resolved w/ $\Pi \to qq'$	$\nu(\nu(qq'))$	[50, 51]	N, Π identification
		Boosted	$\nu\nu J$	[55]	2-prong, no V boson tag, boosted Π deacy
j	J	Fully resolved	$j(jqq')$	n/a	
		Resolved w/ $\Pi \to qq'$	$j(j(qq'))$	n/a	
		Boosted	jjJ	n/a	
c	C	Fully resolved	$c(cqq')$	n/a	
		Resolved w/ $\Pi \to qq'$	$c(c(qq'))$	n/a	
		Boosted	ccJ	n/a	
b	B	Fully resolved	$b(bqq')$	n/a	
		Resolved w/ $\Pi \to qq'$	$b(b(qq'))$	n/a	
		Boosted	bbJ	n/a	
t	T	Fully resolved	$t(\bar{t}qq')$	n/a	
		Resolved w/ $\Pi \to qq'$	$t(\bar{t}(qq'))$	n/a	
		Boosted	$t\bar{t}J$	n/a	

- 8 different final states times 3 possible topologies = 24 distinct signatures
- F quark flavors appear to be completely unexplored
- For F = N, the ν pair stands for the pairs of the SM left-handed neutrino ν_L^e and/or sterile right-handed neutrino ν_R^e, as the latter is a candidate of dark-matter particles

Constraint of the model for F = E

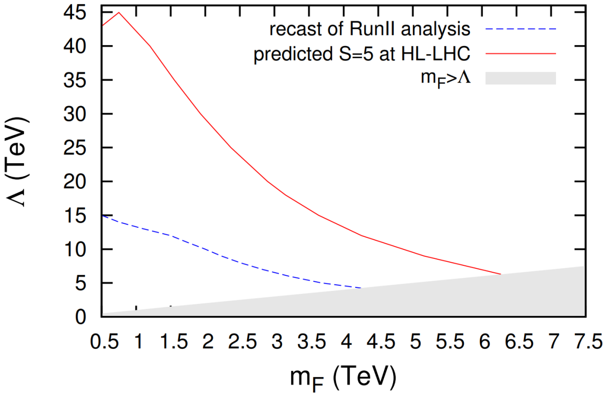
We recast the CMS search (link) that probed the final state eeqq (2.3 /fb, $\sqrt{s}$ = 13 TeV).



Sensitivity for F = E at High-Lumi LHC (3 /ab)

pT e1 (e2) [j1] $\geq$ 180 (80) [210] GeV; $m_{ee} \geq$ 300 GeV

$N_s = L\sigma_s\epsilon_s, \quad N_b = L\sigma_b\epsilon_b, \quad S = \frac{N_s}{\sqrt{N_b}}$



Wide region of the model phase space where the existence of the composite fermions can be investigated (even with a simple analysis)

Summary and conclusion

- New composite states from 4-fermion operators of NJL are well motivated from a theoretical point of view (see e.g. Xue1 Xue2 and references therein)

  Weak coupling regime: 4-fermion NJL operators w/ IR-fixed point that renders the elegant Higgs mechanism at low energies

  Strong coupling regime: 4-fermion NJL operators w/ UV-fixed point that would render F (Π) as bound states of three (two) SM elementary leptons or quarks, and a contact interactions at energies $\mathcal{O}(\mathrm{TeV})$
- We have studied the cross-sections, branching ratios, and topologies with which the F particles can manifest. We find out that

  • for given $\sqrt{s}$ and Λ values, they can be investigated comprehensively relying on only two parameters: F_Π / m_Π and m_Π / m_F

  • 8 different final states times 3 possible topologies = 24 distinct signatures

  • F quark flavors appear to be completely unexplored

  • Even signatures already explored have a wide potential of discovery with the increasing statistics accumulated at the LHC

  • For F = N, the ν pair stands for the pairs of the SM left-handed ν_L^e and/or sterile right-handed ν_R^e neutrinos, as the latter is a candidate of dark-matter particles
- Given the broad variety of new composite particles that could manifest in non-previously examined signatures at the LHC, we would like to encourage their investigations at future searches at the LHC
- There is an ongoing effort to outline the phenomenology for the direct production of composite boson