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

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Physically compelling reasons for 4-fermion operator

- Theoretical inconsistency (NoGo theorem, H. B. Nielsen and M. Ninomiya NPB (1981), NPB (1981), PLB (1981)) of SM bilinear Lagrangian $\bar{\psi}\hat{O}\psi$ in fermion fields in a ultraviolet (UV) cutoff field theory
  $\longrightarrow$ Effective 4-fermion operator of Nambu-Jona-Lasinio (NJL) type $-G(\bar{\psi}_L\psi_R)(\bar{\psi}_R\psi_L)$
  (G. Preparata and S.-S. Xue PLB (1991), S.-S. Xue PLB (1996) , NPB (1997), NPB (2000))

- The effective coupling G has two fixed points:
  (i) In the weak-coupling infrared (IR) fixed point @ the electroweak scale
  - it gives rise to SM physics with tightly composite Higgs particle via the NJL mechanism
  - it offers possible solution to the hierarchy pattern of fermion masses

  (Nambu-Jona-Lasinio PR (1961), PR(1961), W. A. Bardeen, C. T. Hill and M. Lindner PRD (1990), S.-S. Xue, PLB (2013), PLB (2014))
  (ii) In the strong-coupling ultraviolet (UV) fixed point @ at the composite scale Λ ~ O (TeV)
  - composite fermions (bosons) form as bound states of three (two) SM elementary fermions and they couple to their constituents via effective contact interactions

$\longrightarrow$ *Today we focus on LHC phenomenology of such composite fermions*

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
- $\Pi^f \sim (\bar{\psi}^f_R \psi^f_L)$: bound states of *two SM fermions*

The effective coupling between the F (Π) and its constituents is given by the following contact interaction, which describes composite particle production and decay

- $(g_*/\Lambda)^2 \bar{\psi}^f_L (\bar{\psi}^f_L \psi^f_R) F^f_R \ + \ \mathrm{h.c.}$
  Λ = composite scale = O(TeV), $g_*^2 = 4\pi$ and $4\pi/\Lambda^2$ = geometric cross section in the order of magnitude of inelastic processes forming composite fermions
- $(F_\Pi/\Lambda)^2 (\bar{\psi}^f_L \psi^f_R) \Pi^f \ + \ \mathrm{h.c.}$
  $(F_\Pi/\Lambda)^2$ Yukawa coupling between composite bosons and two fermionic constituents

Λ and F_Π are free parameters of the models

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 (1997), S.-S. Xue PRD (2016), JHEP 11(2016)072, JHEP (2017)

Comparison w/ other composite fermions models

Searches for composite fermions @ LHC rely on models such as

J.C. Pati, A. Salam, J.A. Strathdee, Are quarks composite?, Phys. Lett. B 59 (1975) 265, https://doi.org/10.1016/0370-2693(75)90042-8;
H. Harari, Composite models for quarks and leptons, Phys. Rep. 104 (1984) 159, https://doi.org/10.1016/0370-1573(84)90207-2;
O.W. Greenberg, C.A. Nelson, Composite models of leptons, Phys. Rev. D 10 (1974) 2567, https://doi.org/10.1103/PhysRevD.10.2567.
P. A. M. Dirac, Scientific American 208, 45 (1963).
H. Terazawa, K. Akama, and Y. Chikashige, Phys. Rev. D15, 480 (1977).
H. Terazawa, Phys.Rev. D22, 184 (1980).
E. Eichten and K. Lane, Physics Letters B 90, 125 (1980).
E. Eichten, K. D. Lane, and M. E. Peskin, Phys. Rev. Lett. 50, 811 (1983).
H. Terazawa, in Europhysics Topical Conference: Flavor Mixing in Weak Interactions Erice, Italy, March 4-12, 1984 (1984).
N. Cabibbo, L. Maiani, and Y. Srivastava, Phys. Lett. B139, 459 (1984).
U. Baur, M. Spira, and P. M. Zerwas, Phys. Rev. D 42, 815 (1990).
U. Baur, I. Hinchliffe, and D. Zeppenfeld, Int. J. Mod. Phys. A2, 1285 (1987).

Analogies

- the existence of composite fermions
- the existence of contact interaction, in addition to SM gauge interaction, as an effective approach for describing the effects of the unknown internal dynamics of compositeness

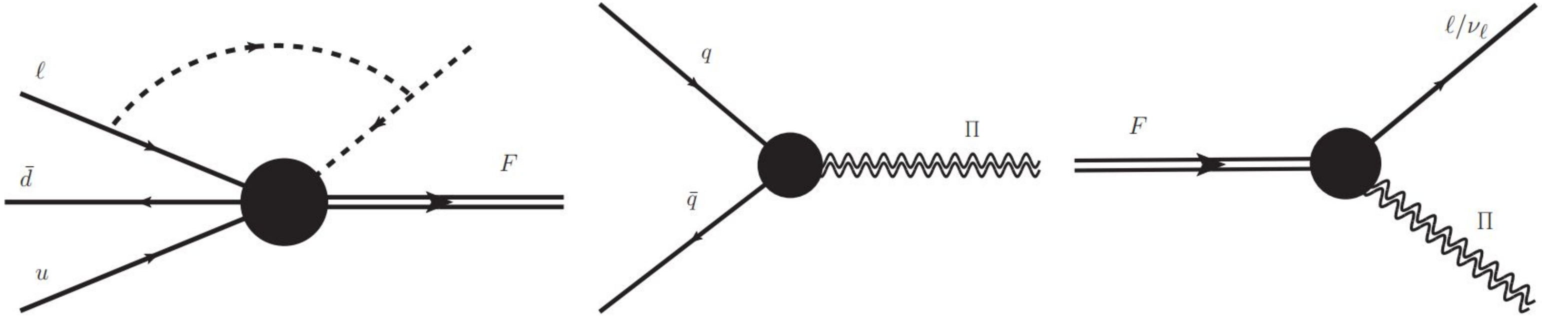
Differences

- composite fermions formed as bound states of SM fermions, not other fundamental particles (preons)
- strong four-fermion interactions of SM fermions at high energies with different contact interacting processes

→ Different phenomenology with a wide range of composite particles that would manifest via peculiar signatures (some of which not yet investigated @ LHC)

Phenomenology of composite particles at the TeV scale

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

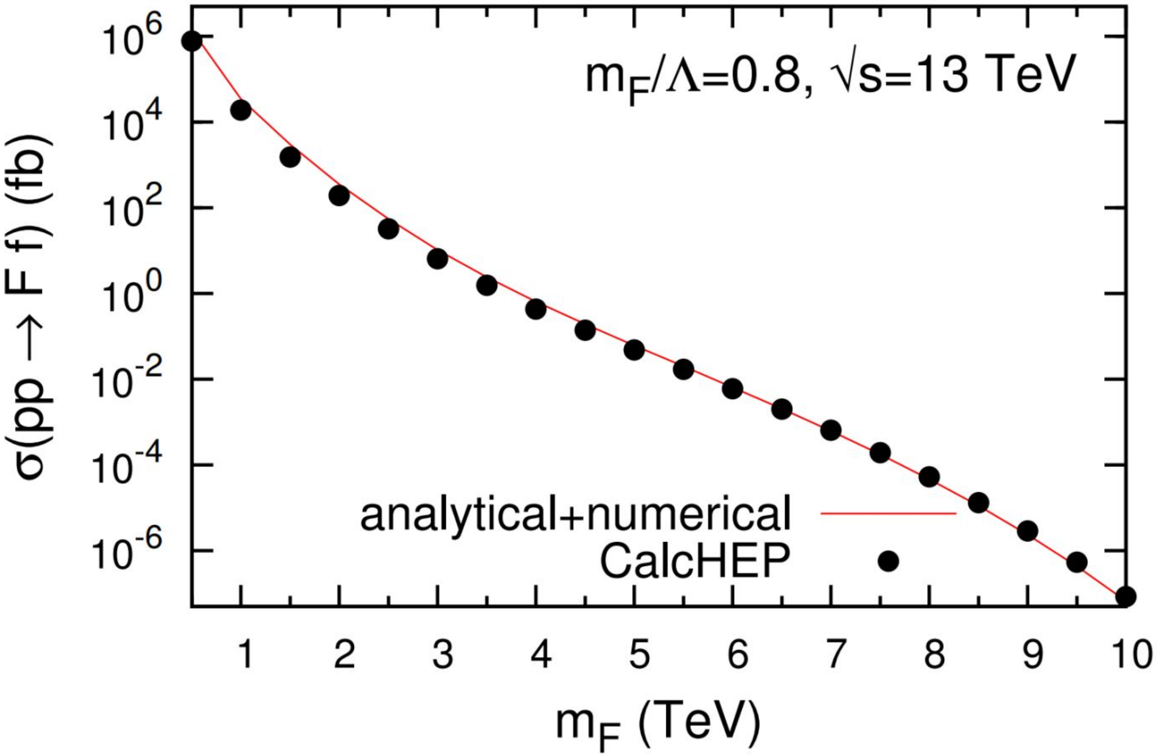


- Today, we describe the phenomenology at the LHC considering the most left diagram
- By a crossing symmetry applied to the fermion line $f \to f^\dagger$ (dashed line) the same diagram describes a $2 \to 2$ production process:

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

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 $pp \to fF$

Decay of the composite 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 $\to fF \to f\bar{f}\, \Pi^{0,\pm}$

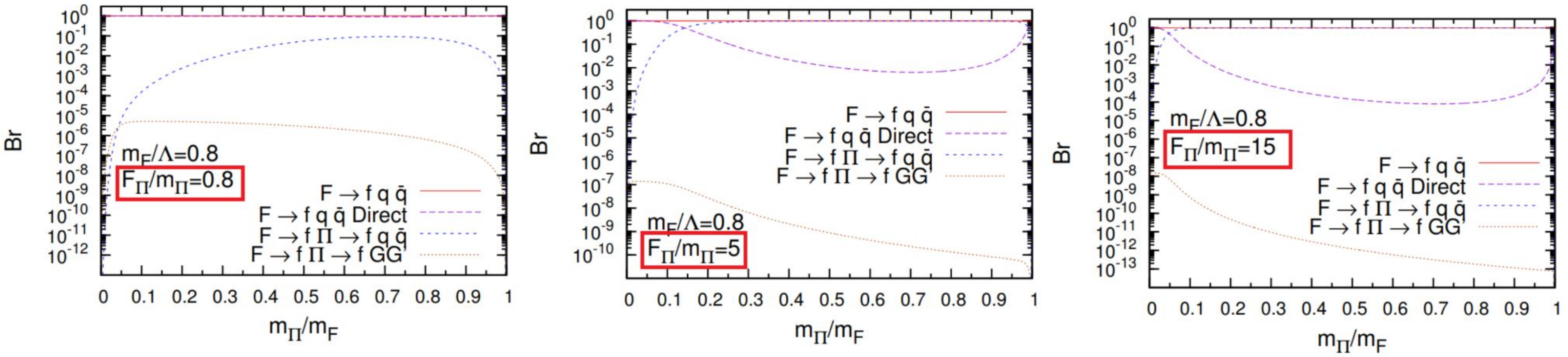
Note that

- 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)

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}

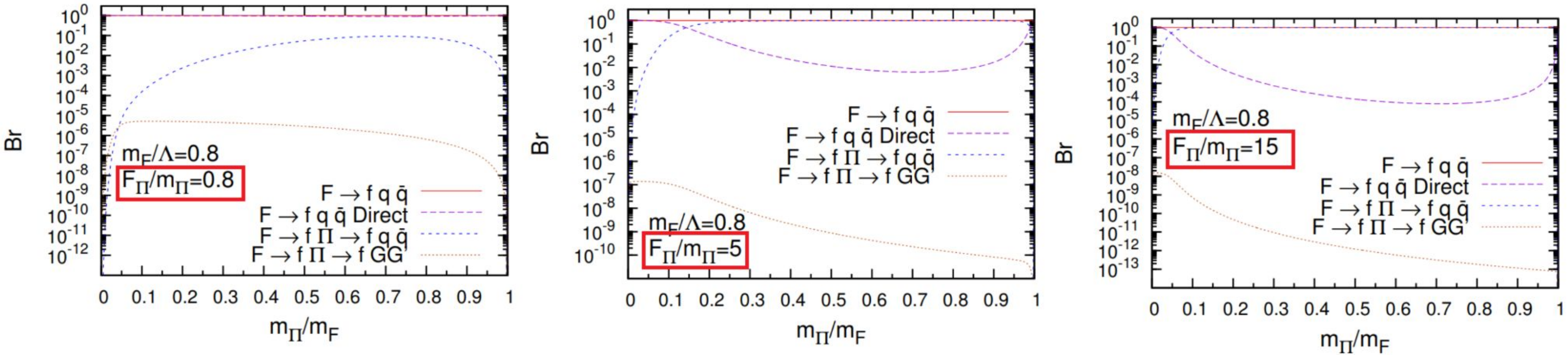
- $m_F/\Lambda < 1$ $(m_\Pi/\Lambda < 1)$: insight into the dynamics of composite fermion (boson) formation
- F_Π/m_Π: m_Π and F_Π represent the same dynamics of composite boson formation
- $m_\Pi/m_F < 1$: to take into account F as composed by a composite boson and an elementary SM fermion

Decay branching fraction 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 LHC

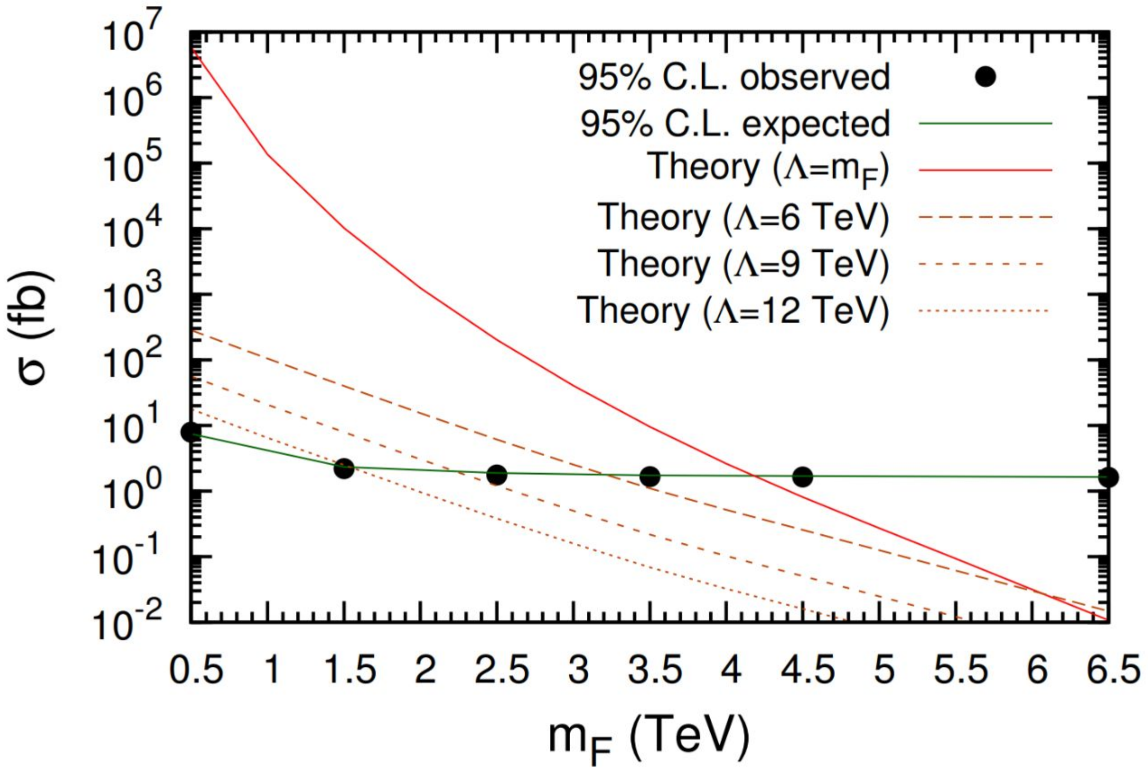
f = SM fermion; F = composite fermion, whose flavour correspond to the SM flavour of f
F particles not necessarily mass degenerate $\to$ each flavour searched for separately

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

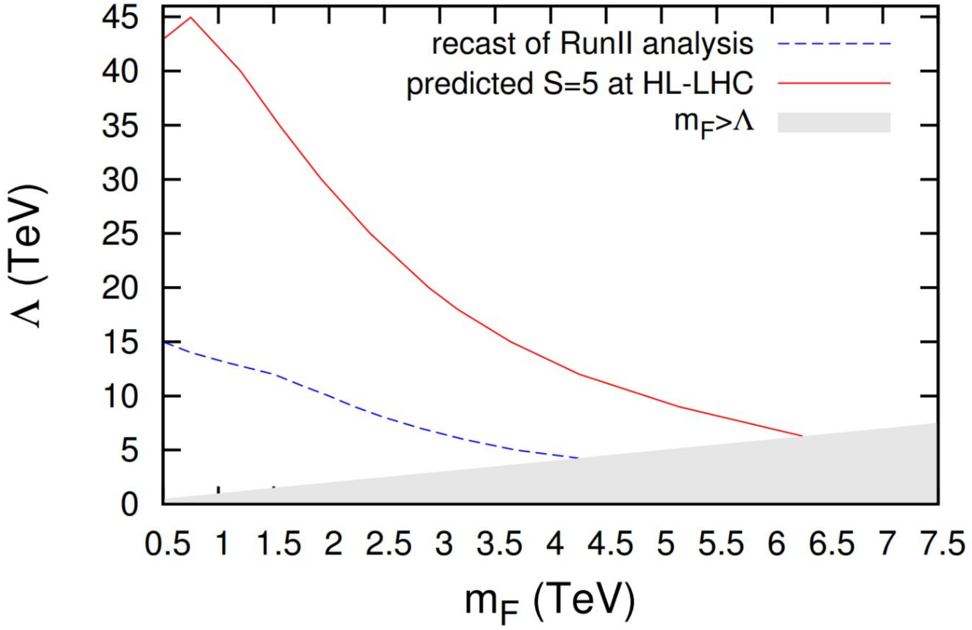
Recast of the CMS search (link) that probed the final state eeqq (2.3 fb^{-1}, $\sqrt{s}$= 13 TeV)



Sensitivity for F = E at High-Lumi LHC (3 ab^{-1})

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

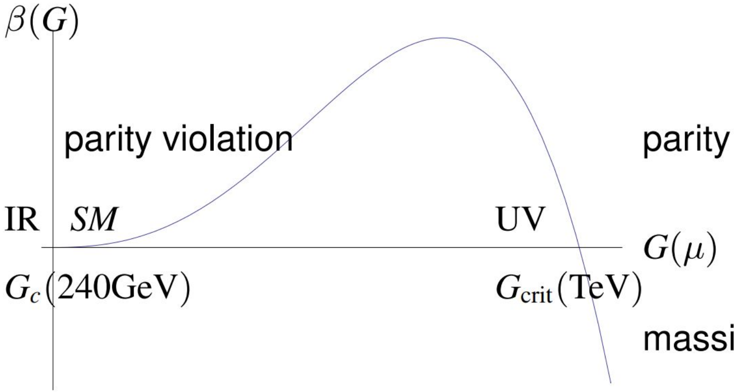
- New composite states from 4-fermion operator of NJL are well motivated from a theoretical point of view (see e.g. S.-S. Xue JHEP (2016), S.-S. Xue JHEP (2017) and references therein)
  - Weak coupling regime: 4-fermion NJL operators w/ IR-fixed point that renders the elegant Higgs mechanism at low 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 O(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 there is a possible candidate of dark-matter particle
- 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

Back up

4-fermion operators and IR UV-fixed points

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.

very weak coupling | parity violation | parity conservation



massive bound states

strong-coupling symmetric phase

symmetric phase | SSB symmetry breaking phase

- 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,$\cdots$.