Strong dynamics beyond the Standard Model at LHC and Future Colliders

Aldo Deandrea
Université Lyon 1

Joint workshop of the FKPPL and TYL/FJPPL
International Associated Particle Physics Laboratories

Jeju island, South Korea - May 8th 2019

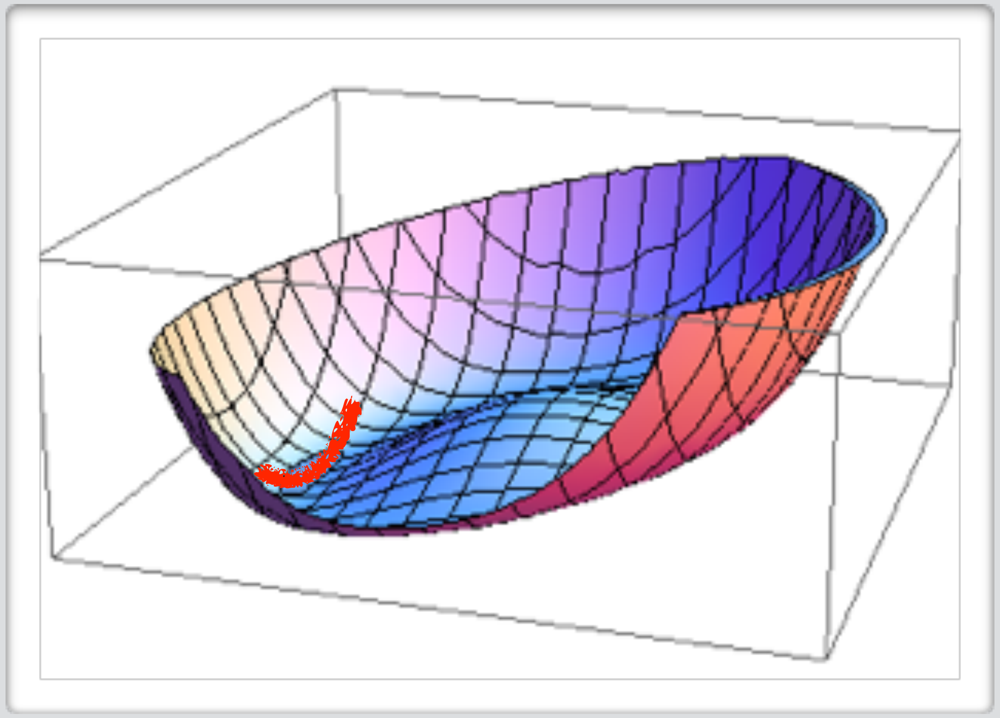
Lyon 1

Proposal for collaboration with FJPPL team:
G.Cacciapaglia, C.Cot, D.Harada, M.Hashimoto, Y.Okada, S.Vatani

Strong dynamics in the EW sector

Global symmetry:

G → H



SU(2)xU(1) → $U(1)_{em}$

SM gauge symmetry

"pions" h, WL, ZL

Higgs boson light as pNGB of the broken symmetry of the strong sector, parameterisation with an effective chiral Lagrangian, detailed computations in terms of the fundamental fermionic states

Fundamental composite dynamics

- Strong dynamics from a confining gauge group G_{TC}:
  - define N fundamental fermions charged under G_{TC}
  - assign SM quantum number to fundamental fermions
  - couple to SM fermions
- The EFT for bound states Lagrangian must respect the symmetries (NOT a generic EFT !)
- Lattice results (if available) determine the spectra and couplings

Which models, which resonances?

coset	GTC	TF	Higgs doublets	pNGBs	
SU(4)/Sp(4)	Sp(2N)	fund	1	5	T.Ryttov, F.Sannino 0809.0713 Galloway, Evans, Luty, Tacchi 1001.1361 ← Minimal!
SU(5)/SO(5)	SU(4)	6	1	14	Dugan, Georgi, Kaplan 1985!!!
SU(4)xSU(4)/SU(4)	SU(N)	fund	2	15	G.C., T.Ma 1508.07014
SU(6)/Sp(6)	Sp(2N)	fund	2	14	G.C., C.Cai, H.Zhang 1805.07619

Which models, which resonances?

- Strong dynamics for the EW sector:
  - spin 1 (popular guess but S parameter needs extra contribution (axial-vector, …), via Drell-Yan mainly, typically heavy
  - spin 0 (new composite scalars, PNGB) already the minimal model contains more than the Higgs!
  - spin 1/2 (new vector-like fermions)
- Extended SM scalar sector, DM candidate
- Extended gauge sector

Scalars in EW strong dynamics

- A light scalar σ mixing with the PNGB Higgs is a general property (see lattice studies)
  - v=f sin (θ) with v EW scale, f composite scale
  - Relation unnatural in Chiral "composite" Higgs as θ very small
  - Relation problematic in Technicolor as θ →π/2
  - Relation natural in fundamental composite Higgs: sin (θ) ≲ 0.6
- A pseudo-scalar "η" with WZW anomaly couplings is present in the spectrum.
  - Couplings are calculable in terms of the dynamics

See hep-ph/1502.04718 for details of the scalar sector in minimal SU(4)/Sp(4) case and hep-ph/0809.0713 for the model; arXiv:1809.09146 for the naturalness study.

Scalars in EW strong dynamics

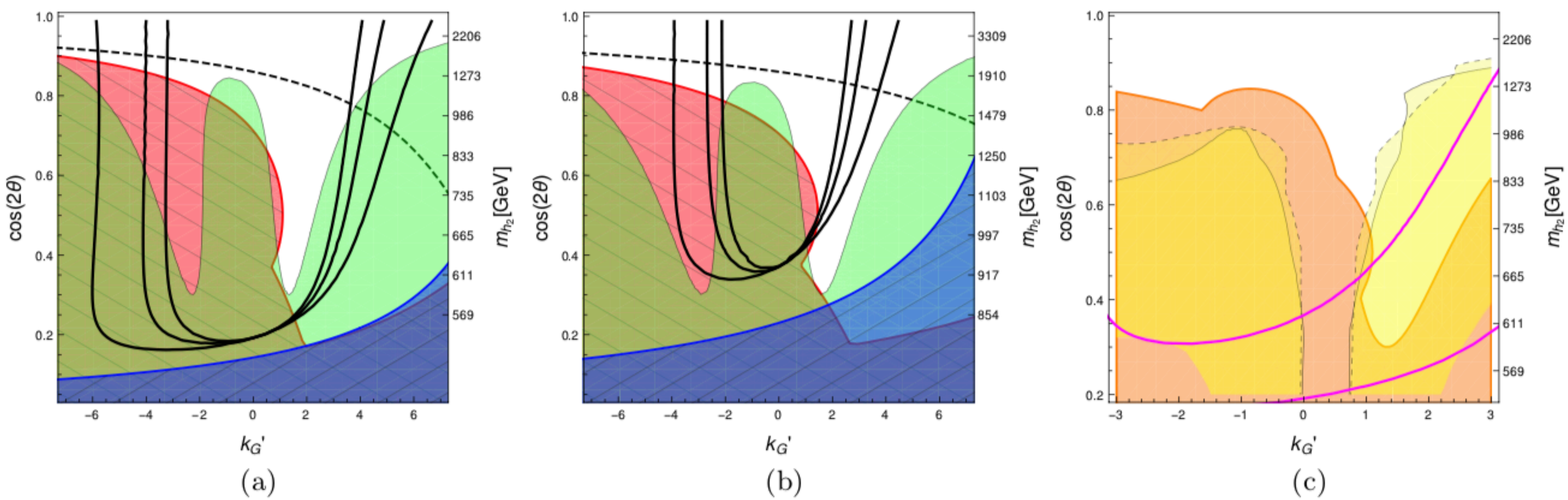


FIG. 1: Excluded regions from indirect (a,b) and direct (c) constraints. In all plots we used $\delta_A = -0.9$, $r = 1.1$, $\widetilde{g} = 3$. Furthermore, in the *left panel* $\gamma = 0.2$, in the *middle panel* $\gamma = 0.3$. In the *right panel* the bound from direct search in ZZ is shown in yellow together with the indirect bounds for $\gamma = 0.2$ and $\kappa_g = s_\theta$.

from arXiv:1809.09146

A toy vector-like model

	$SU(N)$	$SU(3)_c$	$SU(2)_W$	$U(1)_Y$
$Q_L = (Q_1, Q_2)_L$	$\square$	$\mathbf{3}$	$\mathbf{2}$	0
$Q_R = (Q_1, Q_2)_R$	$\square$	$\mathbf{3}$	$\mathbf{2}$	0
$L_L = (L_1, L_2)_L$	$\square$	$\mathbf{1}$	$\mathbf{2}$	0
$L_R = (L_1, L_2)_R$	$\square$	$\mathbf{1}$	$\mathbf{2}$	0
N_L	$\square$	$\mathbf{1}$	$\mathbf{1}$	0
N_R	$\square$	$\mathbf{1}$	$\mathbf{1}$	0

$$N_f = 2N_c n_Q + 2n_L + 1,$$

$$N_f < 11N/(4T(R))$$

to keep asymptotic freedom

η pNGB is in the U(1) part of SU(N)

arXiv:1507.03098

$$\kappa_B^\eta = \kappa_{WB}^\eta = 0,$$

$$\kappa_g^\eta = \frac{1}{2}N(N-1)\cdot 2n_Q,$$

$$\kappa_W^\eta = \frac{1}{2}N(N-1)\cdot (N_c n_Q + n_L),$$

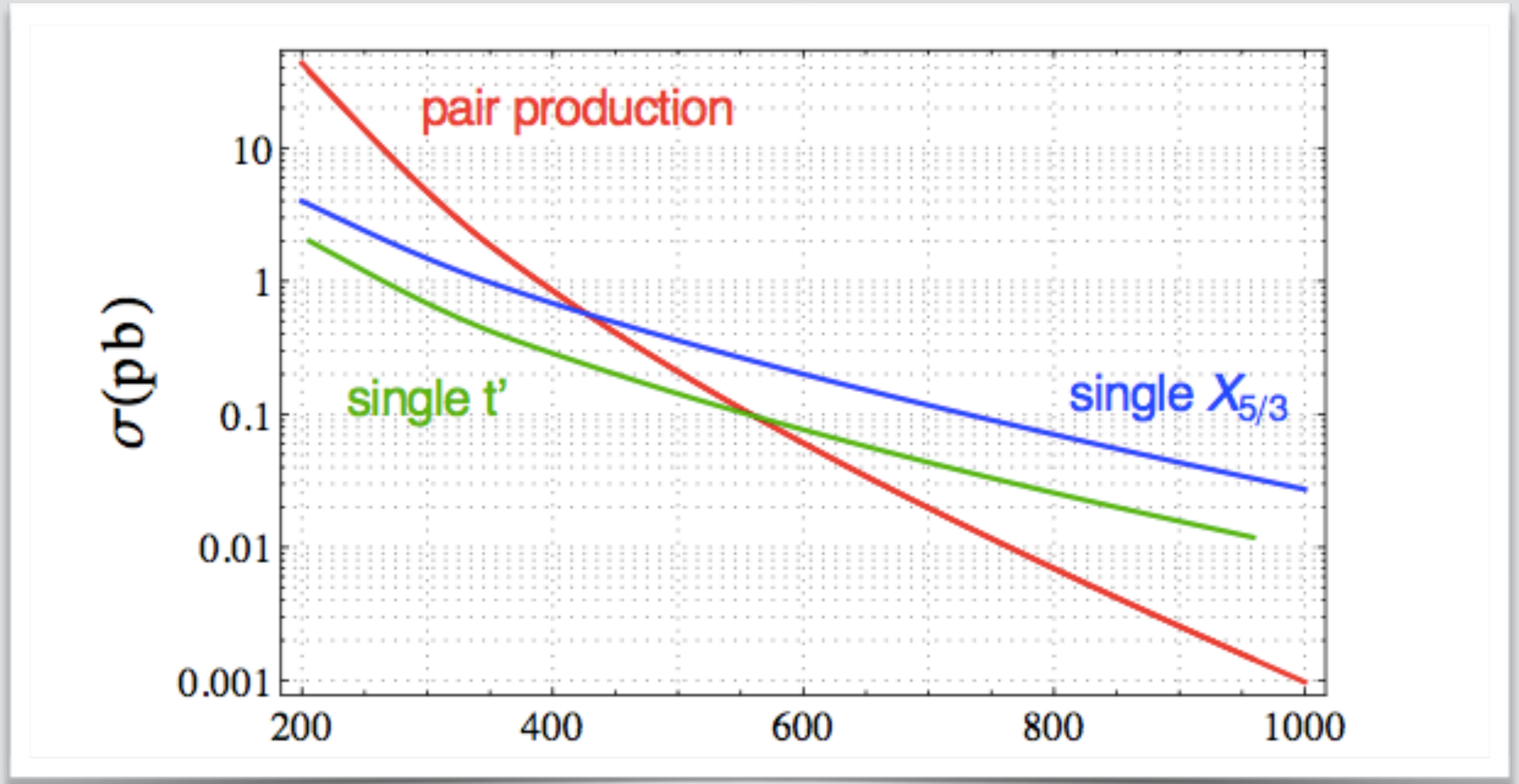
Vector-like quarks

- Unique window to test models (Xdim, composite, Little Higgs, SUSY) and good theoretical motivation

- Reach at LHC substantial and only partially exploited

- Mixings with all the 3 SM generations important (production/decay)

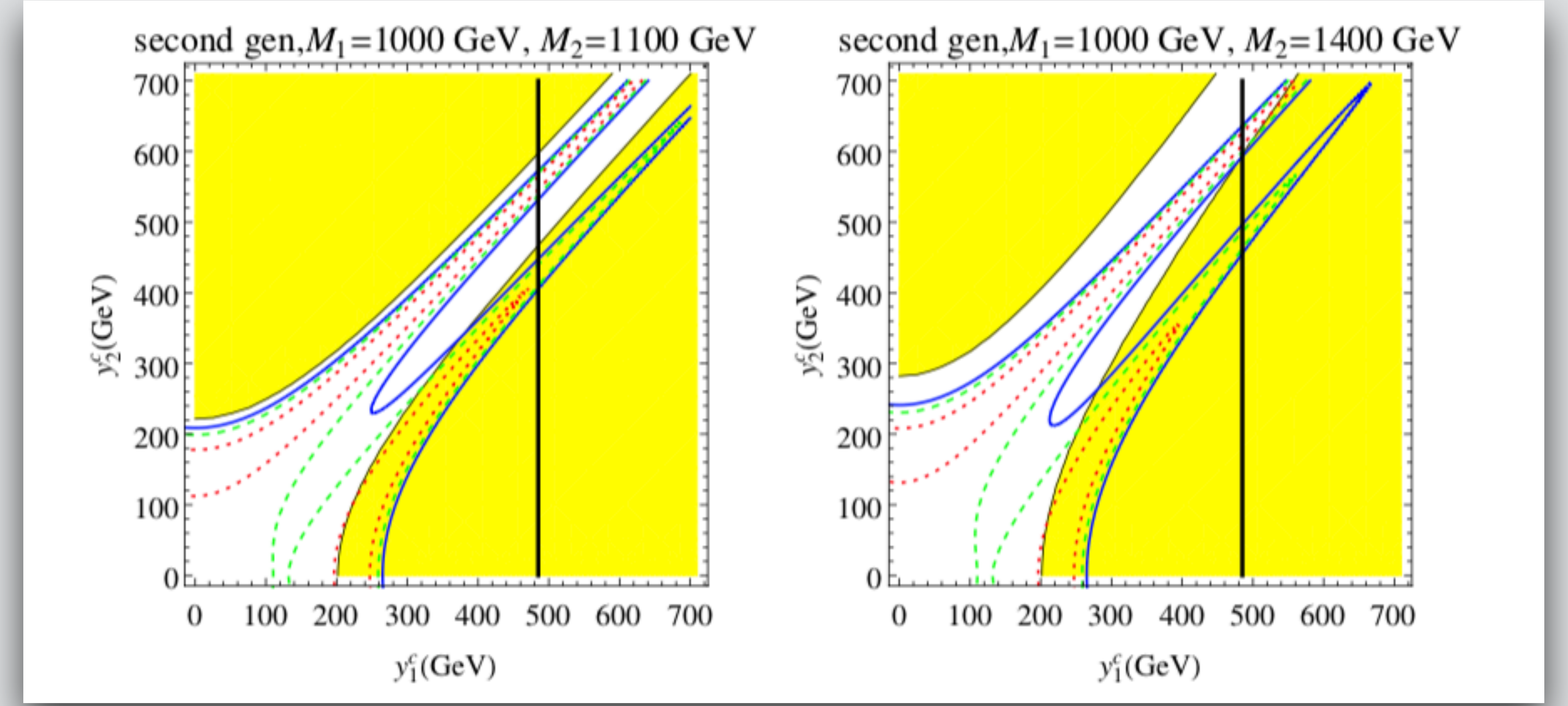
- Single production dominant with present mass bound at LHC (~1 TeV)



Simplest multiplets (and SM quantum numbers)

	SM	Singlets	Doublets	Triplets
	$\begin{pmatrix} u \\ d \end{pmatrix} \begin{pmatrix} c \\ s \end{pmatrix} \begin{pmatrix} t \\ b \end{pmatrix}$	(t') (b')	$\begin{pmatrix} X \\ t' \end{pmatrix} \begin{pmatrix} t' \\ b' \end{pmatrix} \begin{pmatrix} b' \\ Y \end{pmatrix}$	$\begin{pmatrix} X \\ t' \\ b' \end{pmatrix} \begin{pmatrix} t' \\ b' \\ Y \end{pmatrix}$
$SU(2)_L$	2	1	2	3
$U(1)_Y$	$q_L = 1/6$ $u_R = 2/3$ $d_R = -1/3$	2/3 -1/3	1/6 7/6 -5/6	2/3 -1/3
$\mathcal{L}_Y$	$-\frac{y_u^i v}{\sqrt{2}} \bar{u}_L^i u_R^i$ $-\frac{y_d^i v}{\sqrt{2}} \bar{d}_L^i V_{CKM}^{i,j} d_R^j$	$-\frac{\lambda_u^i v}{\sqrt{2}} \bar{u}_L^i U_R$ $-\frac{\lambda_d^i v}{\sqrt{2}} \bar{d}_L^i D_R$	$-\frac{\lambda_u^i v}{\sqrt{2}} U_L u_R^i$ $-\frac{\lambda_d^i v}{\sqrt{2}} D_L d_R^i$	$-\frac{\lambda_i v}{\sqrt{2}} \bar{u}_L^i U_R$ $-\lambda_i v \bar{d}_L^i D_R$
$\mathcal{L}_m$		$-M\bar{\psi}\psi$ (gauge invariant since vector-like)		
Free parameters		4 $M + 3 \times \lambda^i$	4 or 7 $M + 3\lambda_u^i + 3\lambda_d^i$	4 $M + 3 \times \lambda^i$

Interplay of VLQ multiplets (doublets)



Tree level (yellow area is excluded at 3σ), EWPT (blue continuous line corresponds to the 3σ bound, green dashed to 2σ, red dotted to 1σ, the strip between the lines is allowed) and LHC single VLQ production bounds (vertical black line, excluded region on the right) in the case of mixing of two VLQ multiplets with the second SM quark generation.

arXiv:1806.01024

Conclusions and perspectives

- Current limits with the 13 TeV LHC data span up to 1 TeV in mass for vector-like quarks (actual limits depend on the specific decay patterns and possible extra decay modes).
- Scalars/Pseudoscalars may be much lighter and difficult to detect. Specific signatures can be suggested.
- U(1) PNGB (di-bosons), coloured PNGBs (gluon photon), EW PNGBs (W photon, ...)
- New final states for top-partner searches
- We will investigate realistic set-ups and signatures in composite models at the LHC and future colliders.