Vector-like quarks and vacuum misalignment in composite Higgs models

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w/ Gabriele Ferretti

Phys Rev D 107 (2023) 9, 095006

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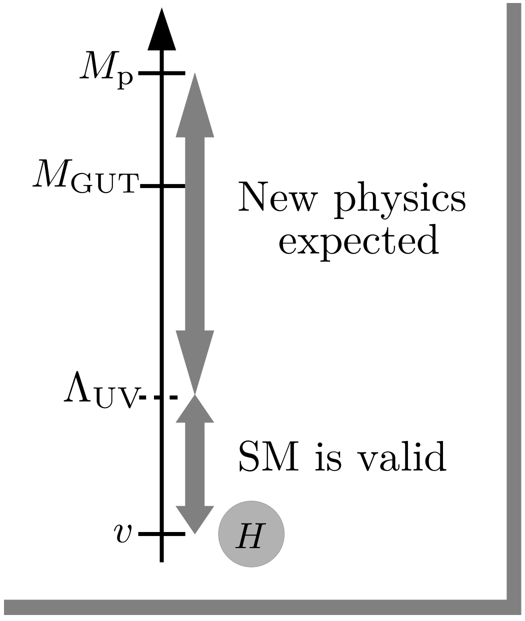
Why Composite Higgs?



$$\delta m_h^2 \simeq \frac{\lambda_i}{16\pi^2}\Lambda_{\rm UV}^2$$

Hierarchy problem

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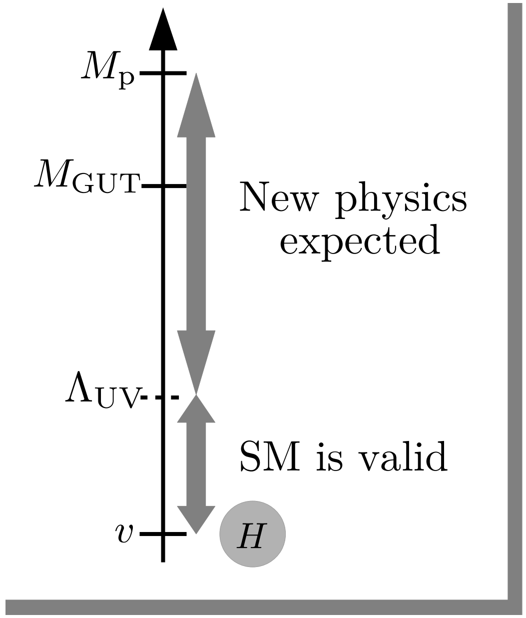

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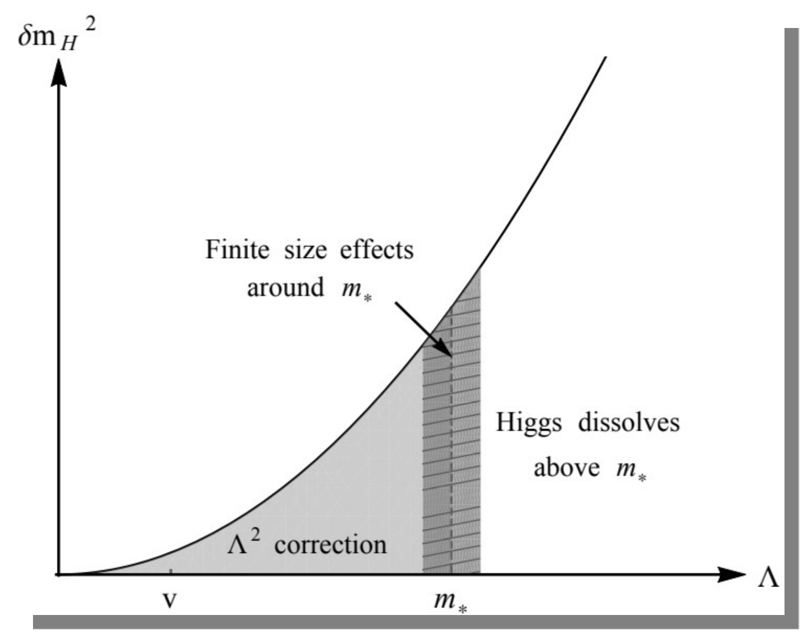
Hierarchy problem



- Higgs boson is a **composite bound state** of a strongly interacting sector

- Similar to pions in QCD, Higgs is **a pseudo Nambu-Goldstone boson (pNGB)**

D B Kaplan, H Georgi, Phys. Lett. B 136 (1984) 183

Overview

- Requirement 1: pNGB Higgs potential must **trigger electroweak symmetry breaking**, give mass to W,Z bosons.

Vacuum misalignment

- Requirement 2: Explain **why top quark is so heavy** compared to 1st and 2nd generation quarks?

Partial compositeness

- Our goal: Connecting vacuum misalignment mechanism with partial compositeness

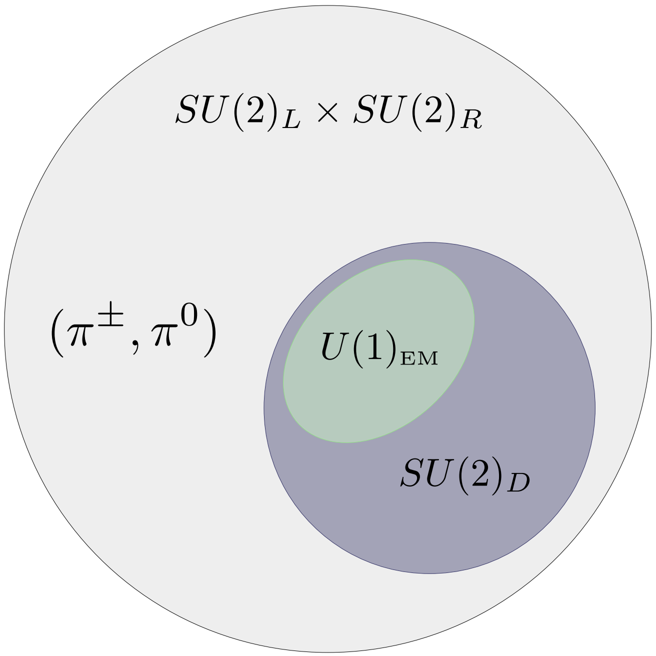
R Contino, Y Nomura, A Pomarol, [hep-ph/0306259], [hep-ph/0412089]

J Barnard, T Gherghetta, T S Ray, [1311.6562]

G Ferretti, D Karateev, [1312.5330],[1404.7137],[1604.06467]

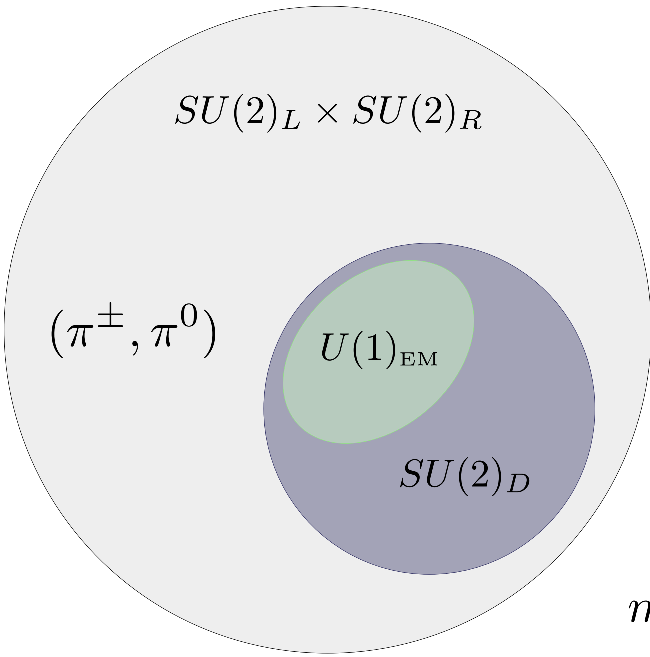
And many more ... ...

Recap: QCD



- Chiral symmetry breaking leads to pions as NGBs
- How do the pions get a potential?

Recap: QCD



- Chiral symmetry breaking leads to pions as NGBs
- How do the pions get a potential?

$$V_\pi = V_q + V_\gamma = \frac{1}{2} m_{\pi^0}^2 (\pi^0)^2 + m_{\pi^\pm}^2 \pi^+ \pi^-$$

$$m_{\pi^0}^2 = -\frac{(m_u + m_d)}{f_\pi^2} \langle q\bar{q} \rangle > 0$$

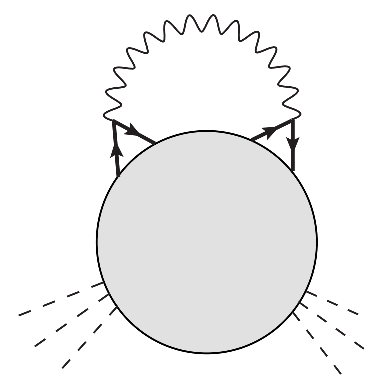
Gellmann-Oakes-Renner, 1968

$$m_{\pi^\pm}^2 - m_{\pi^0}^2 = \frac{3\alpha}{2\pi} m_\rho^2 \ln 2$$

Mathur, Das, Guralnik, 1967

Electromagnetism remains unbroken

Witten, 1983

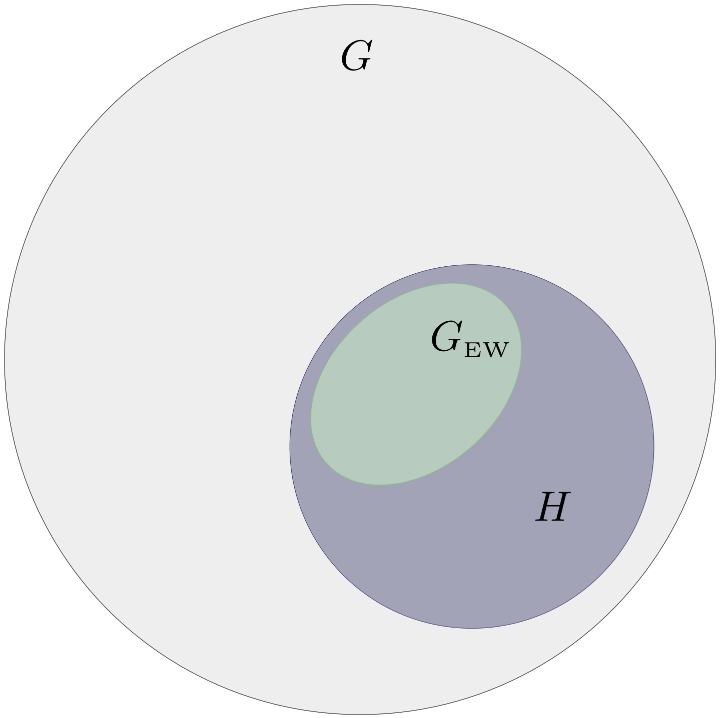


Composite Higgs *vis-a-vis* QCD

$$\mathcal{L}_{\rm SM-H} + \mathcal{L}_{\rm HC} + \mathcal{L}_{\rm d>4} \overset{f\sim{\rm TeV}}{\to} \mathcal{L}_{\rm SM} + \mathcal{L}_{\rm comp} + \mathcal{L}_{\rm int}$$

Properties	QCD	Composite Higgs
Gauge group	$SU(3)_c$	Hypercolor, SU(N) / Sp(N) / SO(N)
Fundamental dof	Quarks, Gluons	Hyperquarks, Hypergluons
Global symmetry	$\frac{SU(3)_L \times SU(3)_R}{SU(3)_D}$	$\frac{SU(N)}{SO(N)}, \frac{SU(N)}{Sp(N)}, \frac{SU(N)\times SU(N)}{SU(N)_D}$
pNGBs $\langle\psi\psi\rangle$	Pions	Higgs + BSM scalars
$\langle\psi\gamma^\mu\psi\rangle$	$\rho-$meson	spin-1 resonances
$\langle\psi\psi\psi\rangle$	Baryons	VLQs (Top-partners)
Partial compositeness	–	Explains quark mass
Vacuum misalignment	–	Triggers EWSB

Composite Higgs vacuum



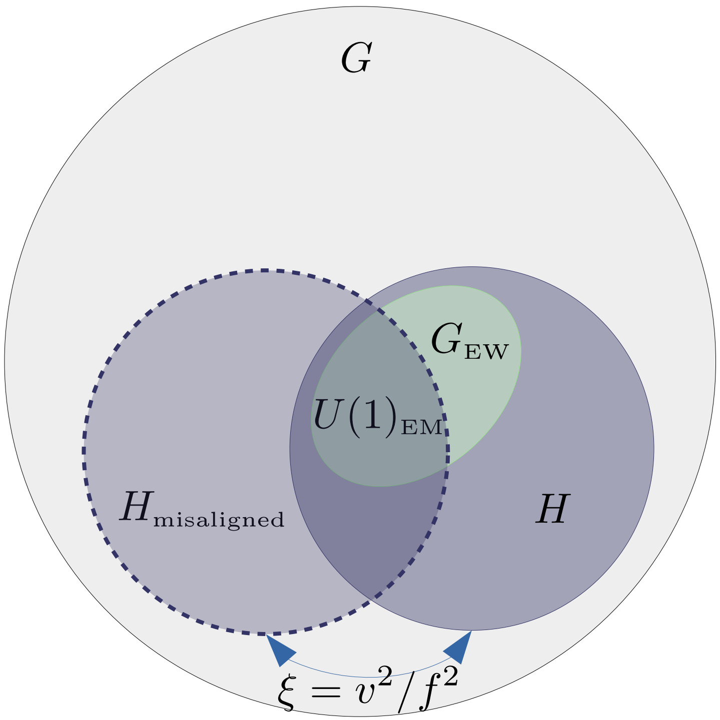
$$\frac{G}{H} \to \frac{\mathrm{SU}(4)}{\mathrm{Sp}(4)}, \ \frac{\mathrm{SU}(5)}{\mathrm{SO}(5)}, \ \frac{\mathrm{SU}(4)\times\mathrm{SU}(4)}{\mathrm{SU}(4)_{\mathrm{D}}}$$

$$H \supset \mathrm{SU}(2)_L \times \mathrm{SU}(2)_R \supset G_{\mathrm{EW}}$$

$$\text{pNGBs} \to \phi_{(2,2)} + \eta_{(1,1)} + \ldots$$

$$\text{EWSB} \overset{?}{\Longrightarrow} G_{\mathrm{EW}} = \mathrm{SU}(2)_L \times \mathrm{U}(1)_Y \to \mathrm{U}(1)_{\mathrm{EM}}$$

Composite Higgs vacuum



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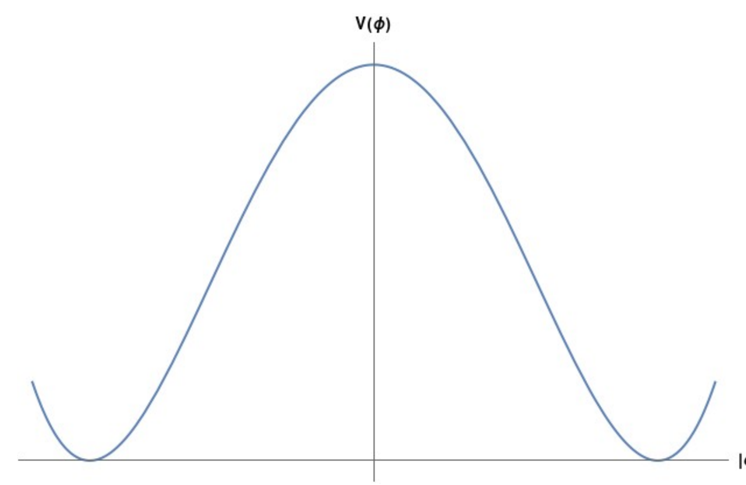
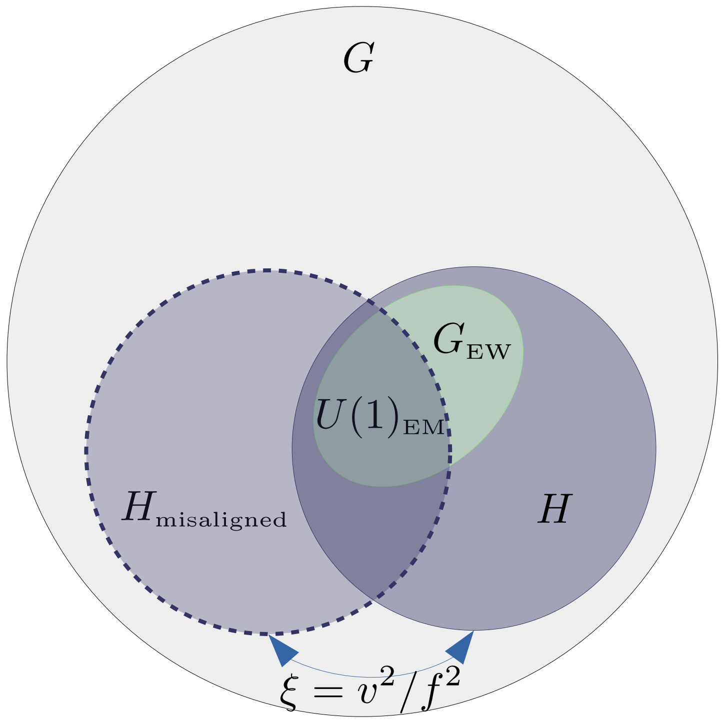
Requirement for EWSB

$$V_\phi \sim -\mu^2 \phi^\dagger \phi + \dots \quad \Longrightarrow \quad \langle \phi \rangle \sim v$$

Tachyonic directions : **vacuum misalignment**



Vacuum misalignment



$$V = V_{\mathrm{mass}} + V_{W,Z} + V_{\mathrm{t}}$$

Hyperquark mass

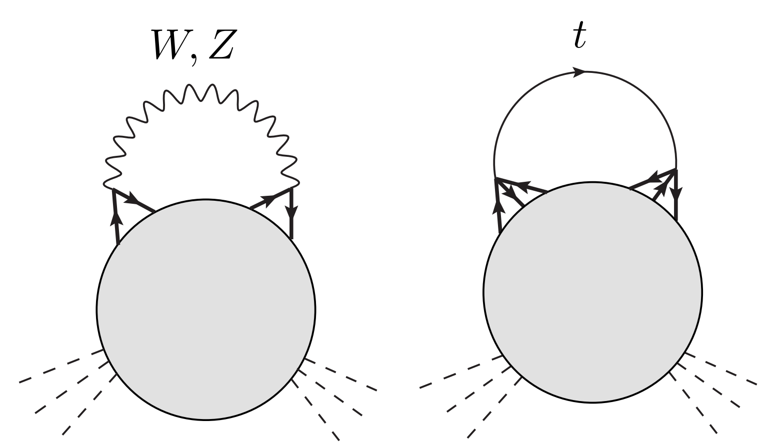
Gauge

Top quark partial compositeness

Similar to QCD hyperquark mass and gauge contributions to V can not misalign the vacuum

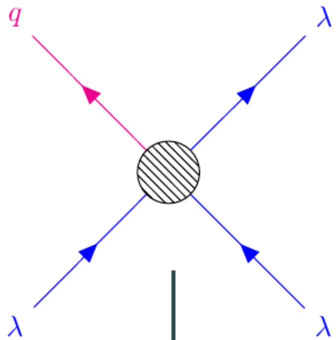
$$V_{\mathrm{mass}} + V_{W,Z} \sim +\mu_m^2 \phi^\dagger \phi + \ldots$$

$$V_t \sim C(\mu_1^2 - \mu_2^2)\phi^\dagger \phi + \ldots$$



AB, G Ferretti, Phys.Rev.D 107 (2023) 9, 095006

Partial compositeness

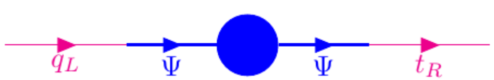


$$\sim \frac{c_{\rm UV}^2}{\Lambda_{\rm UV}^2}\, q\lambda^3 \qquad \Lambda_{\rm UV} \gg \Lambda_{\rm HC} \sim 4\pi f$$

$$\text{Vector} - \text{like quark}: \Psi \equiv \lambda^3$$

$$\sim c_{\rm UV}^2 \left(\frac{\Lambda_{\rm HC}}{\Lambda_{\rm UV}}\right)^{2-\gamma} \Lambda_{\rm HC}\, q\Psi \sim y\Lambda_{\rm HC}\, q\Psi$$

EWSB

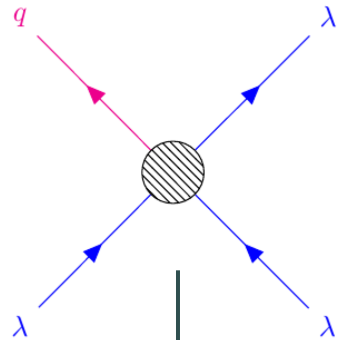


$$\propto y_L y_R v \sim 173 \text{ GeV}$$

Requirements:

- Nearly conformal dynamics above confinement scale
- Large anomalous dimension to reproduce top mass

Partial compositeness



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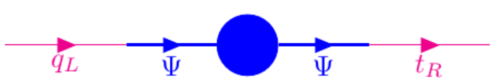

$\propto y_L y_R v \sim 173$ GeV

Requirements:

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- Large anomalous dimension to reproduce top mass

- Physical states are mixture of elementary and composite degrees of freedom
- Top quark is more composite compared to lighter quarks

Vacuum misalignment *via* 4-Fermi operators

$$\boxed{V_t \sim C(\mu_1^2 - \mu_2^2)\phi^\dagger\phi + \ldots}$$

$$\Psi \overset{G/H}{\rightarrow} \Psi_{R_1} + \Psi_{R_2} \quad \Longrightarrow \quad y_1\, t\Psi_{R_1} + y_2\, t\Psi_{R_2}$$

$$\boxed{V_t \sim C\mu^2(y_1^2 - y_2^2)\phi^\dagger\phi + \ldots}$$

$$C = f(M_1, M_2) : \text{Non}-\text{perturbative, sign undetermined}$$

$SU(N)$	$\rightarrow$	$SO(N)$
$\mathbf{Ad}$		$\mathbf{Ad} + \mathbf{S}_2$
$\mathbf{S}_2$		$\mathbf{1} + \mathbf{S}_2$
$SU(2N)$	$\rightarrow$	$Sp(2N)$
$\mathbf{Ad}$		$\mathbf{Ad} + \mathbf{A}_2$
$\mathbf{A}_2$		$\mathbf{1} + \mathbf{A}_2$
$SU(N) \times SU(N)$	$\rightarrow$	$SU(N)$
$(\mathbf{F}, \mathbf{F})$		$\mathbf{A}_2 + \mathbf{S}_2$
$(\mathbf{F}, \bar{\mathbf{F}})$		$\mathbf{1} + \mathbf{Ad}$

Regardless of the overall sign, tachyonic directions can exist

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Regardless of the overall sign, tachyonic directions can exist

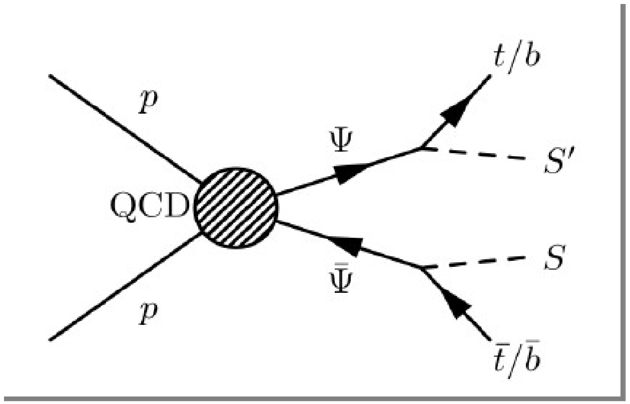
$$C \sim \int \frac{d^4k}{(2\pi)^4} \int d\mu^2 \frac{\rho_1(\mu^2, M_1^2) - \rho_2(\mu^2, M_2^2)}{k^2 + \mu^2}$$

Lattice calculations can in principle determine the overall sign:

- estimate mass spectrum of the VLQs
- determine which irrep leads to misalignment

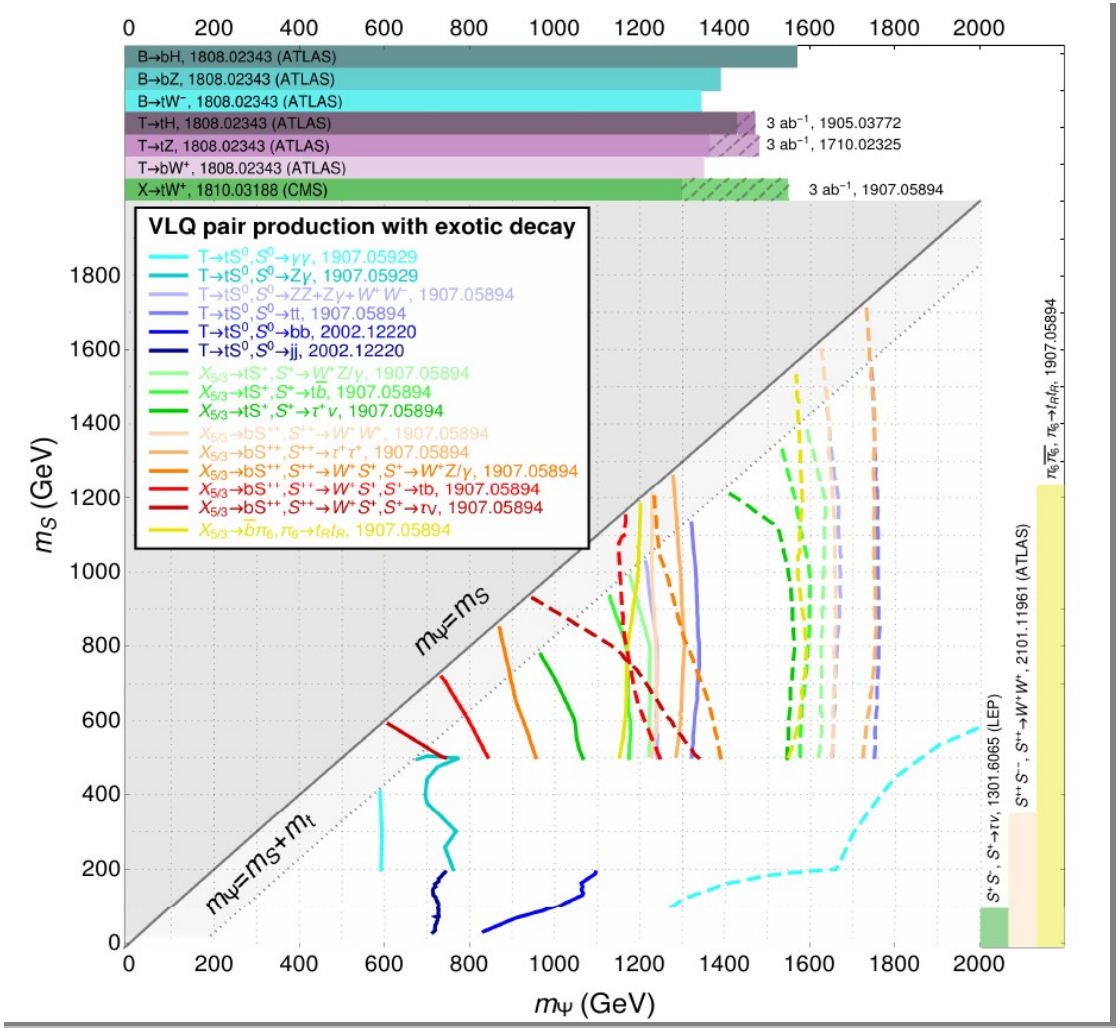
Ed Bennett et. al. Phys. Rev. D 106, 014501
V. Ayyar et. al. Phys. Rev. D 97, 114505

Vector-like quarks @LHC



Limitations:

- Simplified model framework (often with single VLQ)
- Interacting only with SM states
- 100% BR to specific SM channels
- Narrow width approximation

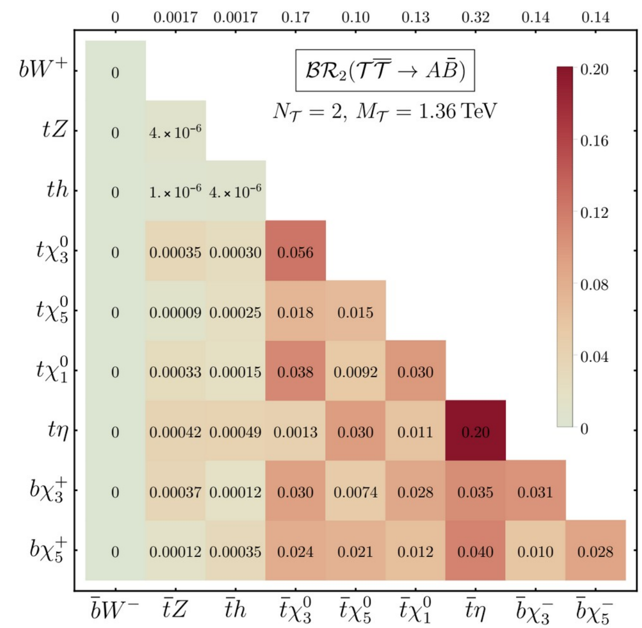


AB, D B Franzosi, G Ferretti, L Panizzi et al [2203.07270]

BSM decays of VLQs

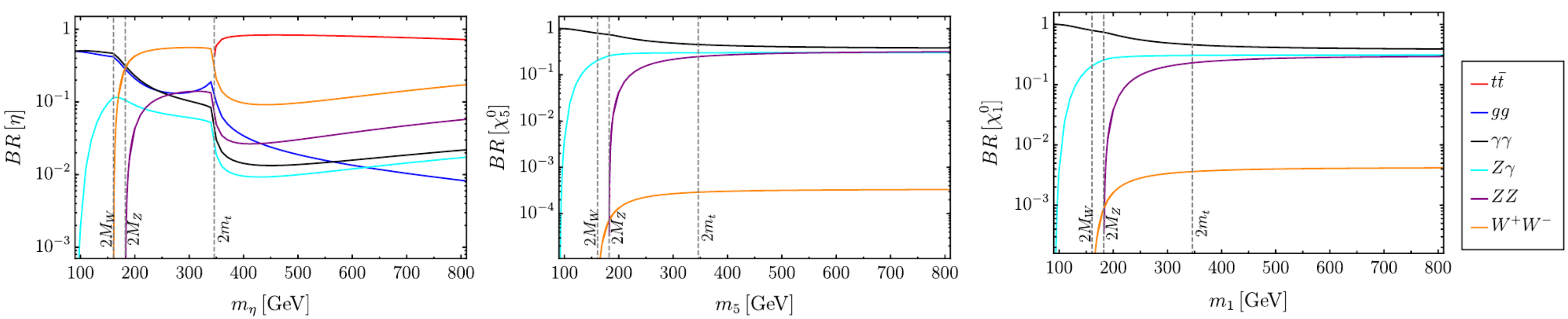
$$pp \to T_{2/3}\bar{T}_{2/3} \to (tS^0) + X \to (t\gamma\gamma) + X$$

Ongoing ATLAS search in diphoton final states
[SHIFT collaboration]



Benchmark composite Higgs coset: SU(5)/SO(5)

$$\sigma(M_T = 1.3\ \text{TeV}) \sim [1 - 10]\text{fb},$$

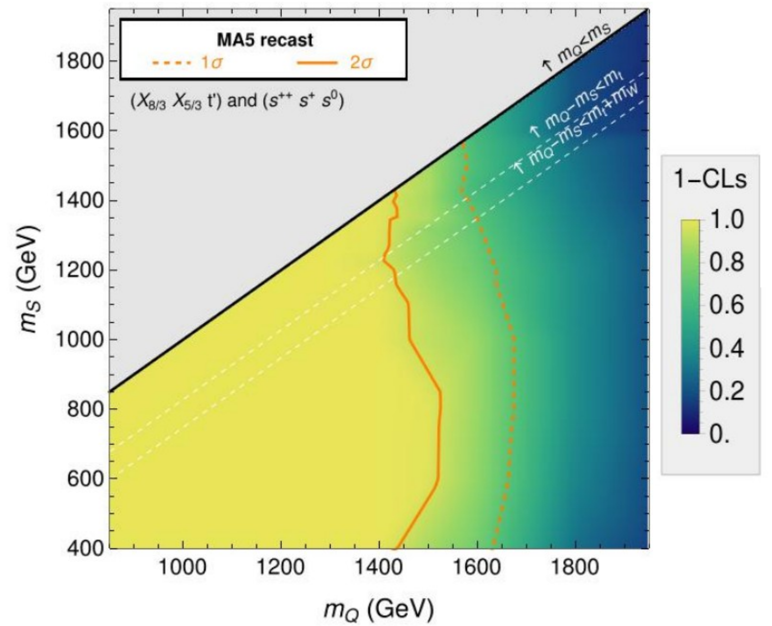


AB, D B Franzosi, G Ferretti, JHEP 03 (2022) 200

BSM decays of VLQs

$$pp \to X_{8/3}\bar{X}_{8/3} \to (tS^{++})\,(\bar{t}S^{--}) \to (2t\,\bar{b}W^{+})\,(2\bar{t}\,bW^{-})$$

- Aim: searching $(\Psi \in 3_{5/3}) \to t + (S \in 3_{\pm 1})$
- Cosets: SO(5)/SO(4), SU(5)/SO(5)
- Interesting feature: Existence of $X_{8/3} \to t + S^{++}$
- Challenge: How to isolate its signal from SM + other VLQ backgrounds? Machine learning?



AB, R Enberg, V Ellajosyula, L Panizzi [work in progress]

https://feynrules.irmp.ucl.ac.be/wiki/NLOModels :Vector like quarks + exotic pNGBs

AB, D B Franzosi, G Ferretti, L Panizzi et al [2203.07270]

Summary

- **Partial compositeness** interactions are necessary to trigger electroweak symmetry breaking through **vacuum misalignment**.

- Major predictions involve existence of **colored vector-like quarks** which can be searched at the LHC.

- **Lattice studies** can shed some light on the **spectrum of VLQs** and the mechanism of EWSB.

- **Strong constraints** from the VLQ searches at the LHC under specific assumptions, upcoming searches in **new channels** will reveal more.

Thank you!