

VACUUM MISALIGNMENT AND VECTOR-LIKE QUARKS IN COMPOSITE HIGGS MODELS

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Overview

- Requirements: pNGB Higgs potential must **trigger electroweak symmetry breaking**.

Vacuum misalignment

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

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

Partial compositeness

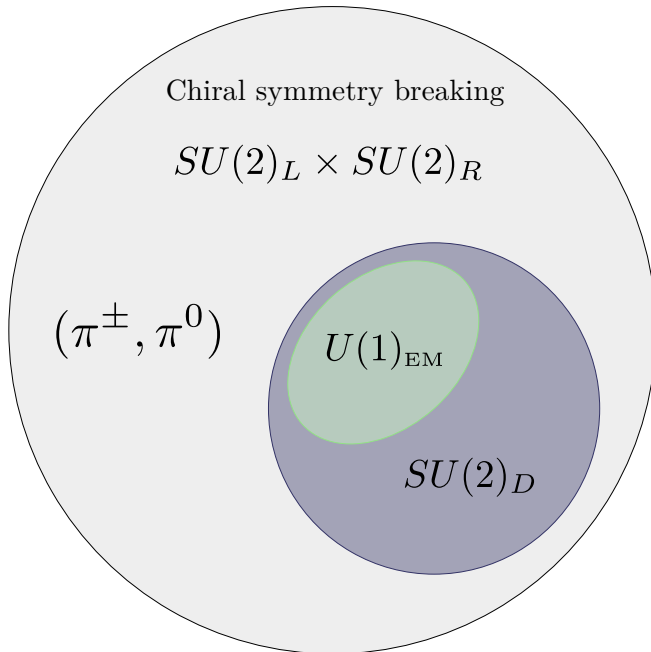
AB, D B Franzosi, G Ferretti, JHEP 03 (2022) 200

- Our goal: Connecting vacuum misalignment mechanism with partial compositeness

Recap: QCD

- Explicit breaking leads to pion potential

$$V_\pi = \Pi \langle \text{vac} | \mathcal{H} | \text{vac} \rangle \Pi$$



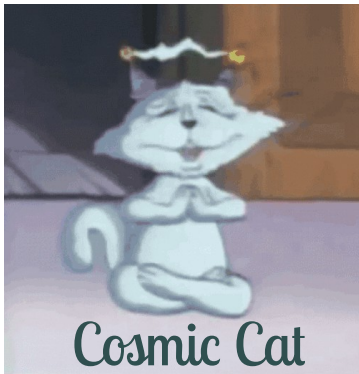
$$V_\pi = V_q + V_\gamma = \frac{1}{2} m_{\pi^0}^2 (\pi^0)^2 + m_{\pi^\pm}^2 \pi^+ \pi^-$$

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

Gellmann-Oakes-Renner, 1968

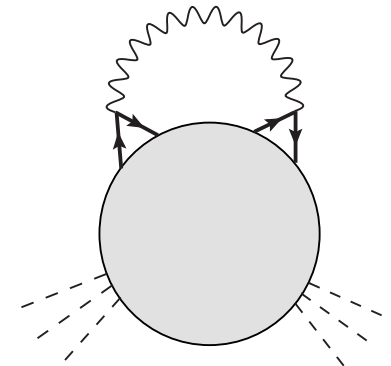
$$m_{\pi^\pm}^2 - m_{\pi^0}^2 = \frac{3\alpha}{2\pi} m_\rho^2 \ln 2$$

Mathur, Das, Guralnik, 1967

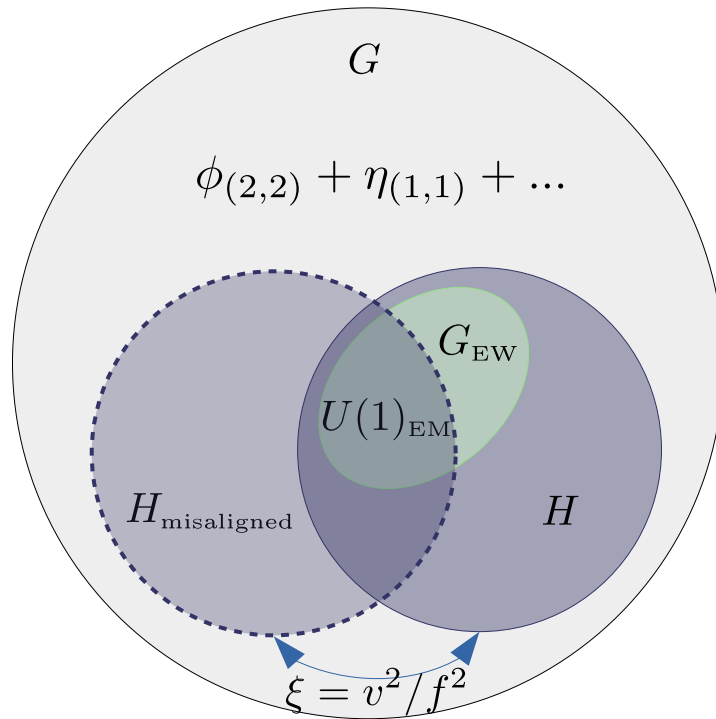


Electromagnetism remains unbroken

Witten, 1983

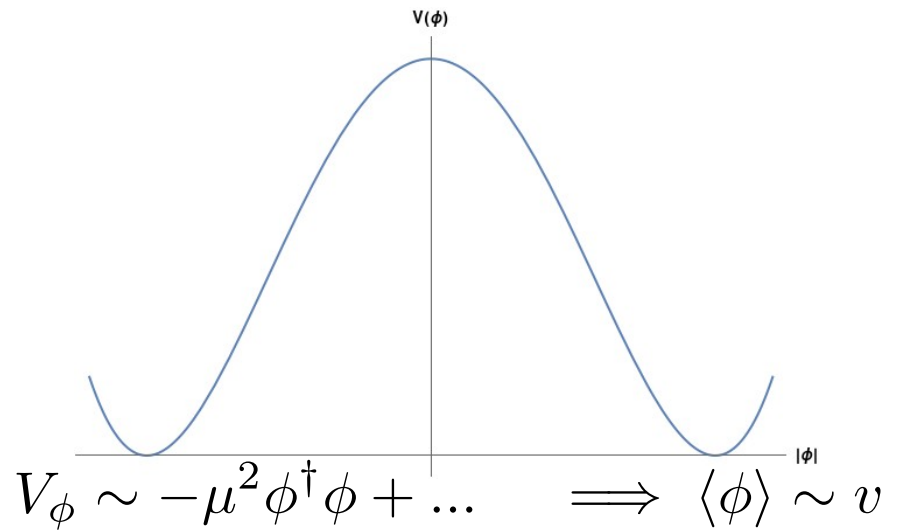


Composite Higgs vacuum

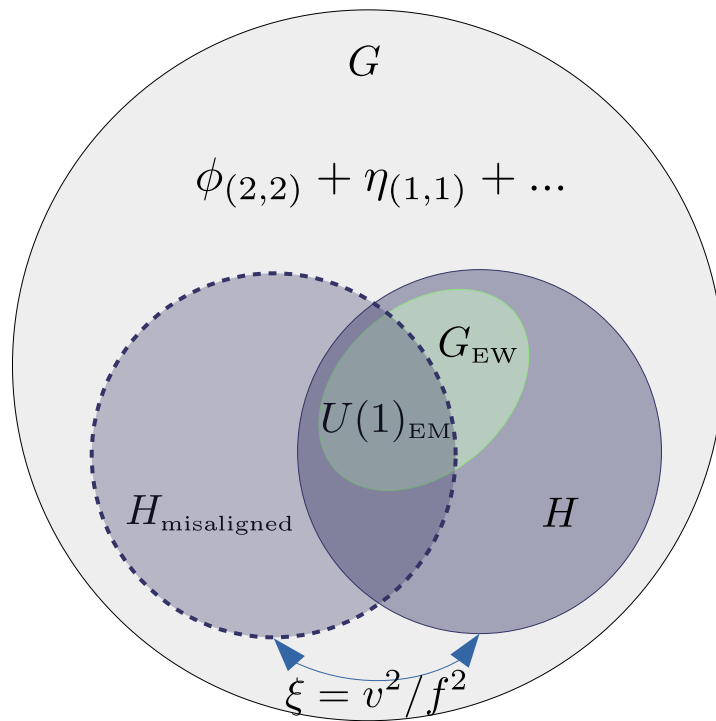


$$\frac{G}{H} \rightarrow \frac{\text{SU}(4)}{\text{Sp}(4)}, \frac{\text{SU}(5)}{\text{SO}(5)}, \frac{\text{SU}(4) \times \text{SU}(4)}{\text{SU}(4)_\text{D}}$$

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

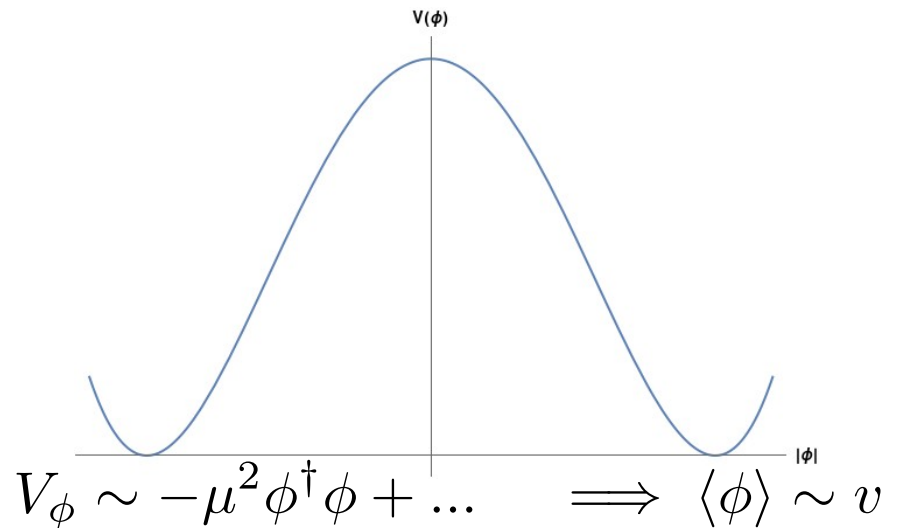


Composite Higgs vacuum



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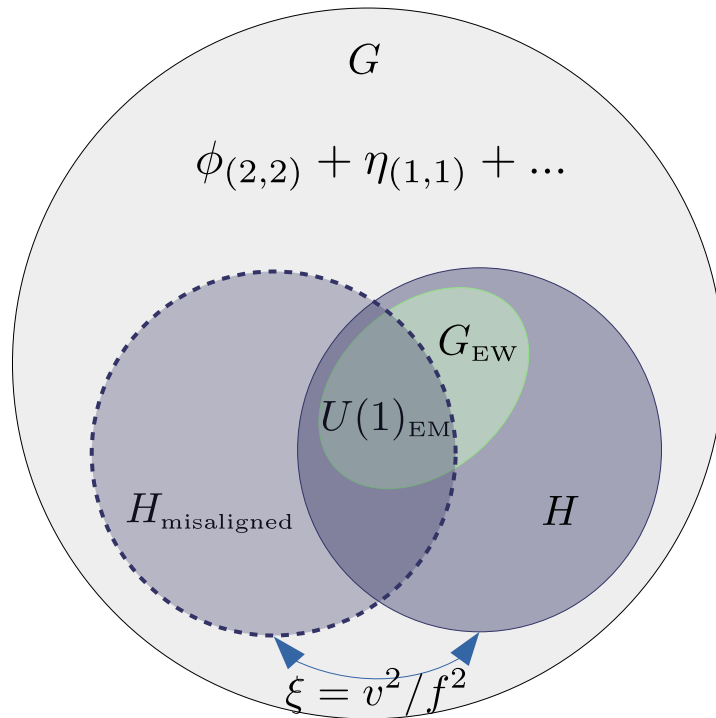
Analyze the potential around origin:

$${}_0 \langle \text{vac} | [Q^{\hat{a}}, \mathcal{H}] | \text{vac} \rangle_0 = 0, \quad (\text{"no-tadpole condition"})$$

$$(M^2)^{\hat{a}\hat{b}} = -\frac{1}{f^2} {}_0 \langle \text{vac} | [Q^{\hat{a}}, [Q^{\hat{b}}, \mathcal{H}]] | \text{vac} \rangle_0 \geq 0 \quad (\text{"no-tachyon condition"})$$

Tachyonic directions : **vacuum misalignment**

Vacuum misalignment



$$V = \Pi \langle \text{vac} | \mathcal{H} | \text{vac} \rangle \Pi$$

$$= V_{\text{mass}} + V_{W,Z} + V_t$$

Hyperquark
mass

Gauge

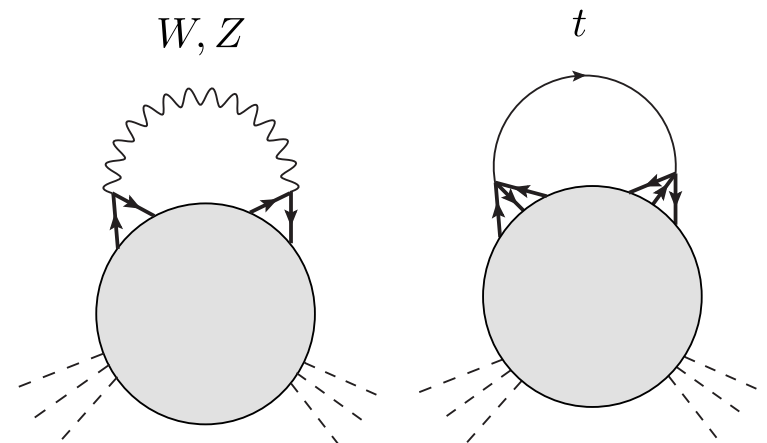
Top quark partial
compositeness

Similar to QCD V_{mass} and $V_{W,Z}$ can not misalign

$$V_{\text{mass}} + V_{W,Z} \sim +\mu^2 \phi^\dagger \phi + \dots$$

$$V_t \sim C\mu^2(\kappa_1^2 - \kappa_2^2)\phi^\dagger \phi + \dots$$

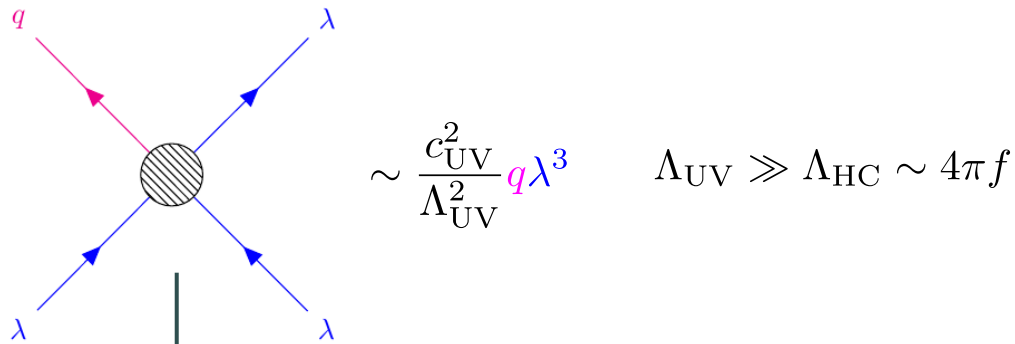
AB, G Ferretti, Phys.Rev.D 107 (2023) 9, 095006



NLO Example: M Golterman, Y Shamir, Phys.Rev.D 91 (2015) 9, 094506

Partial compositeness

[See Gabriele Ferretti's talk also]



Vector – like quark : $\Psi \equiv \lambda^3$

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

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

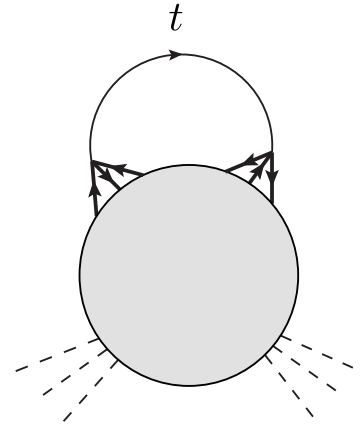
- Physical states are mixture of elementary and composite degrees of freedom
- Top quark is more composite compared to lighter quarks

Vacuum misalignment *via* 4-Fermi operators

$$\Psi \xrightarrow{G/H} \Psi_{R_1} + \Psi_{R_2} \implies \kappa_1 t \Psi_{R_1} + \kappa_2 t \Psi_{R_2}$$

$$\mathcal{H}_{\text{PC}} = -\frac{i}{2} \int d^4x \Delta^{\dot{\alpha}\alpha}(x) T \left\{ \mathcal{K}_R^\dagger \Psi_\alpha^R(x) \Psi_{Q\dot{\alpha}}^\dagger(0) \mathcal{K}^Q + \text{h.c.} \right\}$$

$$V_t \sim C \mu^2 (\kappa_1^2 - \kappa_2^2) \phi^\dagger \phi + \dots$$



$SU(N)$	\rightarrow	$SO(N)$	
Ad		Ad + S ₂	$\text{tr}(\mathcal{P}U\mathcal{P}^*U^*)$
S ₂		1 + S ₂	$\text{tr}(\mathcal{P}U^*)\text{tr}(\mathcal{P}^*U)$
$SU(2N)$	\rightarrow	$Sp(2N)$	
Ad		Ad + A ₂	$\text{tr}(\mathcal{P}U\mathcal{P}^*U^*)$
A ₂		1 + A ₂	$\text{tr}(\mathcal{P}U^*)\text{tr}(\mathcal{P}^*U)$
$SU(N) \times SU(N)$	\rightarrow	$SU(N)$	
(F , F)		A ₂ + S ₂	$\text{tr}(U\mathcal{P}^T U^* \mathcal{P}^\dagger)$
(F , $\overline{\mathbf{F}}$)		1 + Ad	$\text{tr}(\mathcal{P}U^\dagger)\text{tr}(\mathcal{P}^\dagger U)$

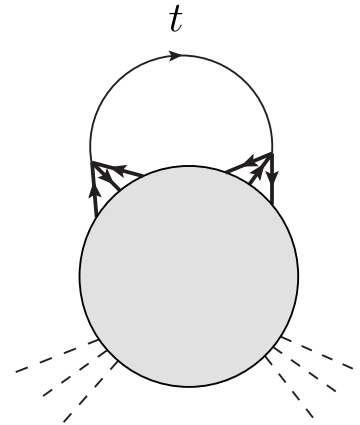
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$$V_t \sim C \mu^2 (\kappa_1^2 - \kappa_2^2) \phi^\dagger \phi + \dots$$

Sign undetermined



Regardless of the overall sign, tachyonic directions can exist

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

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

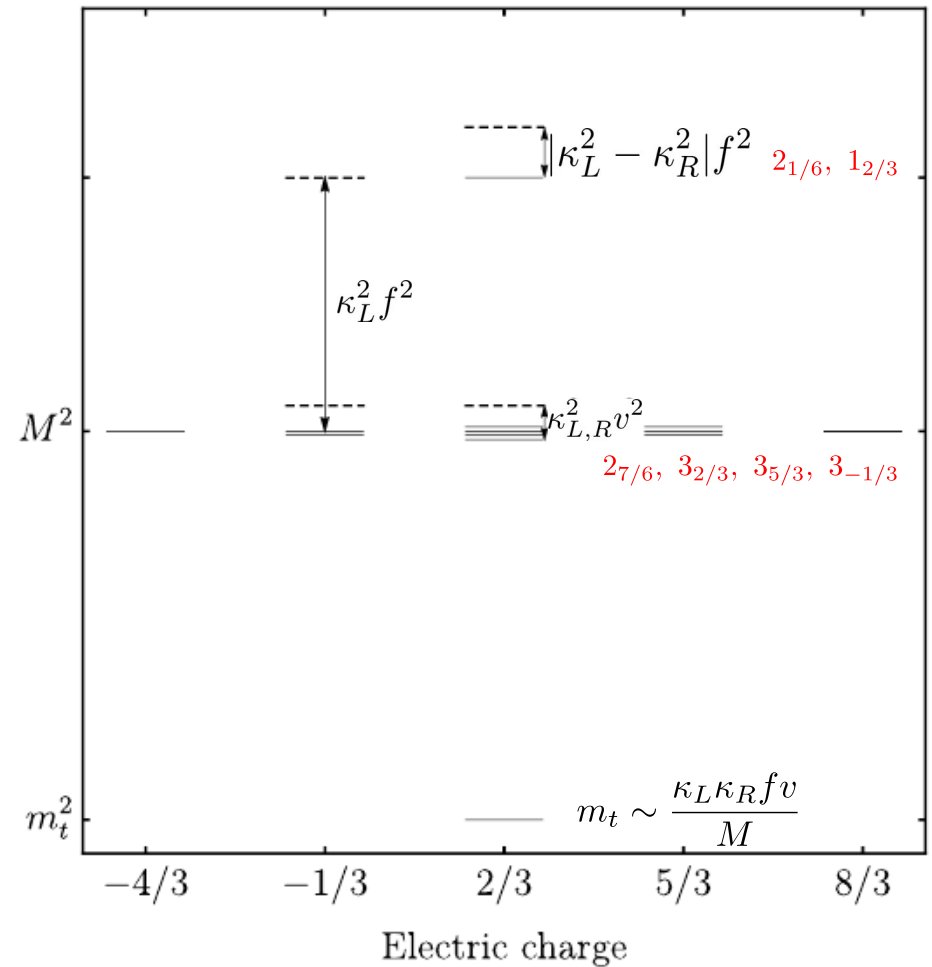
- Lattice calculations can **in principle** determine the overall sign dictating which irrep leads to misalignment

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

Vector-like quark spectrum

$$\begin{pmatrix} \bar{u}_L^1 \\ \bar{u}_L^2 \\ \bar{u}_L^3 \\ \frac{\bar{T}_L^1}{T_L^1} \\ \cdot \\ \cdot \\ \cdot \\ \bar{T}_L^n \end{pmatrix}^T \begin{pmatrix} \begin{array}{c|c} \begin{array}{c} \text{Feynman diagrams for } y_{3 \times 3}^{ij} v \text{ and } \kappa_L^i f \mathcal{F}_L(\frac{v}{f}) \end{array} & \begin{array}{c} \text{Feynman diagrams for } \kappa_R^j f \mathcal{F}_R(\frac{v}{f}) \text{ and } M \mathbb{1}_n \end{array} \\ \hline \begin{array}{c} \text{Feynman diagrams for } \kappa_R^j f \mathcal{F}_R(\frac{v}{f}) \text{ and } M \mathbb{1}_n \end{array} & \begin{array}{c} \text{Feynman diagrams for } y_{3 \times 3}^{ij} v \text{ and } \kappa_L^i f \mathcal{F}_L(\frac{v}{f}) \end{array} \end{array} \begin{pmatrix} u_R^1 \\ u_R^2 \\ u_R^3 \\ \frac{T_R^1}{T_R^1} \\ \cdot \\ \cdot \\ \cdot \\ T_R^n \end{pmatrix}$$

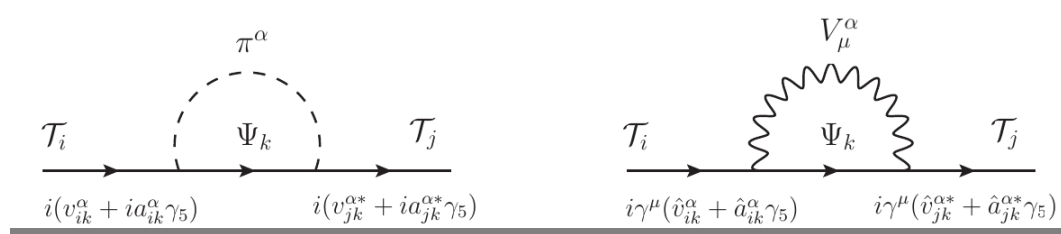
$$m_{1,2} \sim yv \quad m_3 \sim \frac{\kappa_L \kappa_R f v}{M} + yv \gg yv$$



- Spectrum is **generic** (little dependence on a specific model)
- Exotic states are **lighter** and tree-level **degenerate**
- **One-loop mass splitting** and **off-diagonal self-energy**

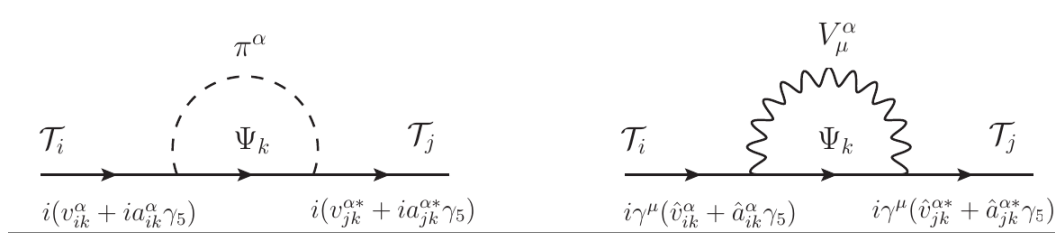
Overlapping resonance states

- Degenerate states are the **lightest** with **off-diagonal** terms in self energy
- One loop mass-splitting can be comparable to the decay widths

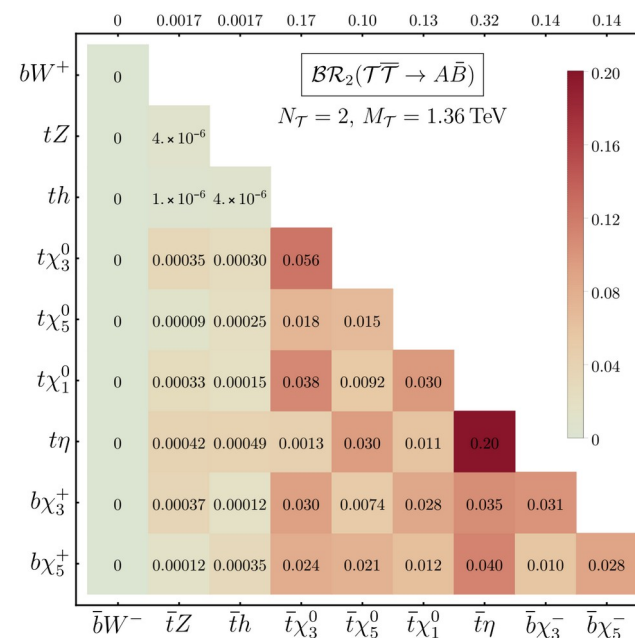
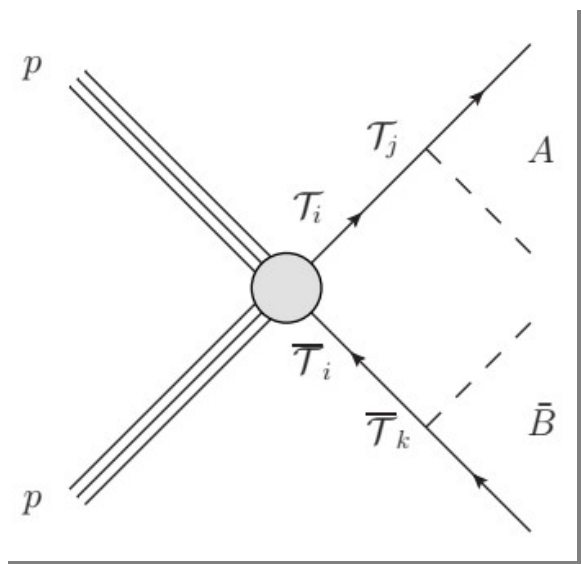


Overlapping resonance states

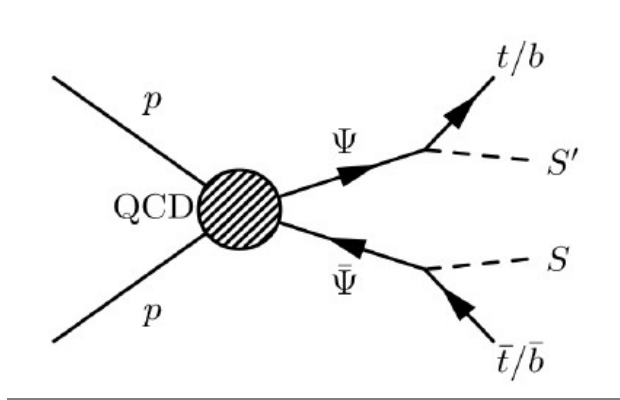
- Degenerate states are the **lightest** with **off-diagonal** terms in self energy
- One loop mass-splitting can be comparable to the decay widths



- **Quantum interference** leads to **correlations between final states** in a pair production process

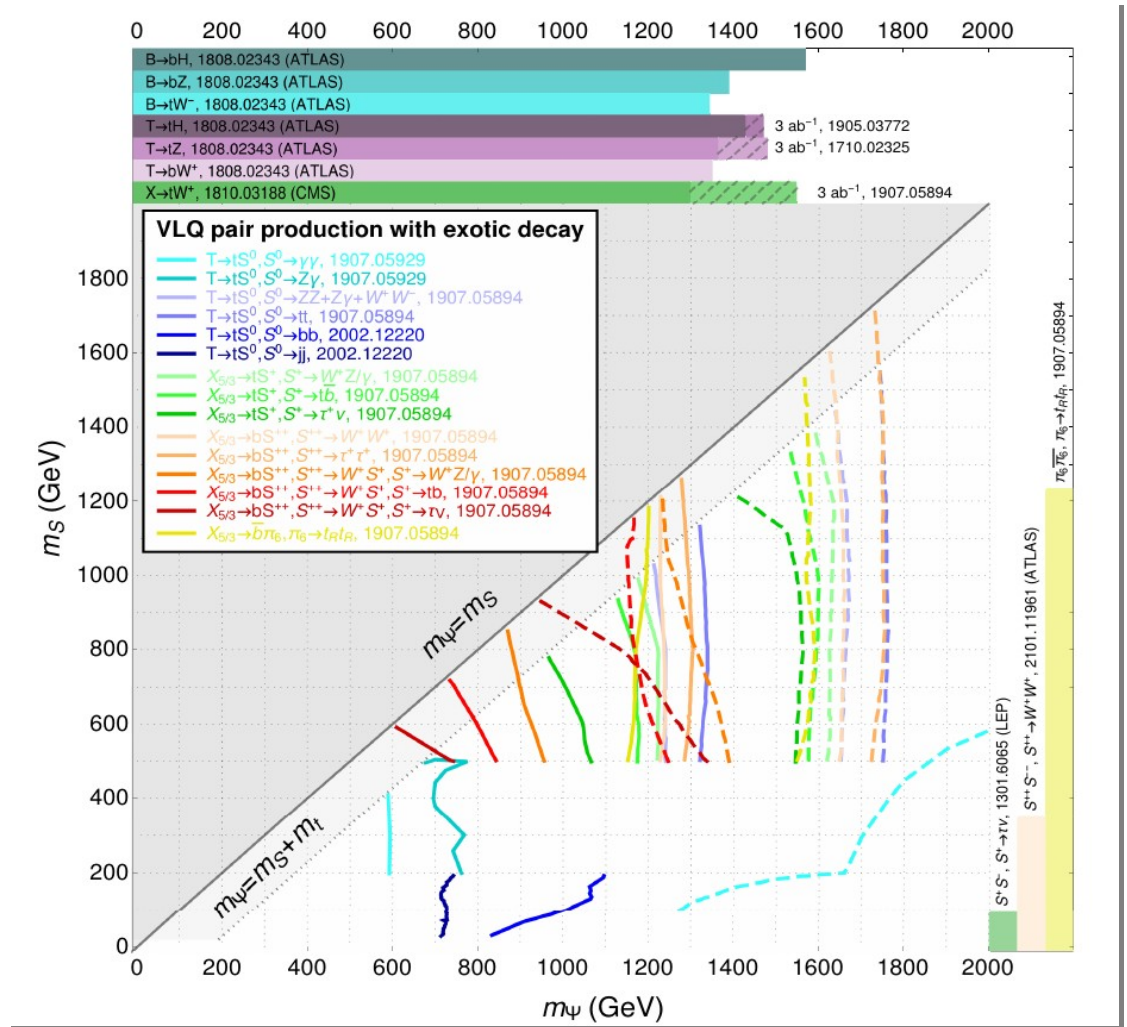


Vector-like quarks @LHC



Limitations/ Rooms for improvement:

- Simplified model framework
- 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]

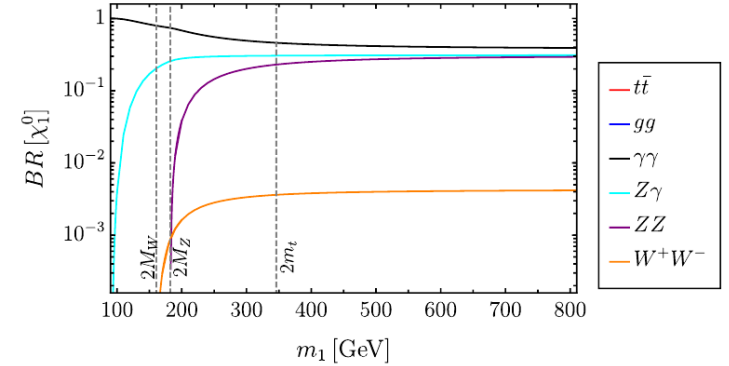
BSM decays of VLQs

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

Ongoing ATLAS search in **diphoton** final states

Benchmark coset: $SU(5)/SO(5)$

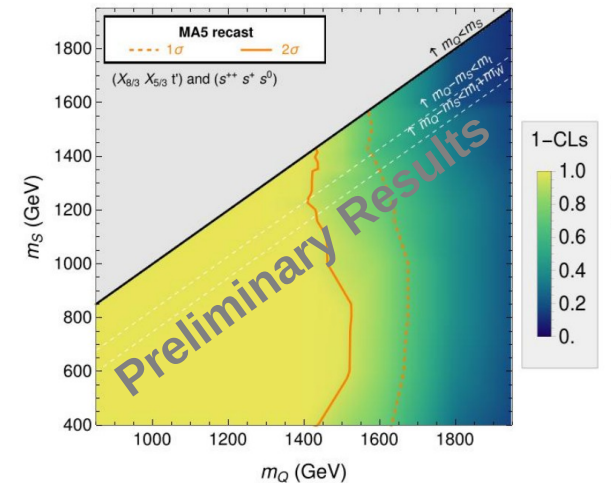
$$\sigma(M_T = 1.3 \text{ TeV}) \sim [1 - 10] \text{ fb},$$



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

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

- Aim: searching $(\Psi \in 3_{5/3}) \rightarrow t + (S \in 3_{\pm 1})$
- Interesting feature: $X_{8/3} \rightarrow t + S^{++}$



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

Summary

- **Partial compositeness** interactions are necessary to trigger electroweak symmetry breaking through **vacuum misalignment**.
- Major predictions involve existence of **colored vector-like quarks** with generic spectrum, **lattice studies** required for more information
- **Strong constraints** from the VLQ searches at the LHC under specific assumptions, upcoming searches in **new channels** will reveal more.

Thank you!