Composite Higgs models

bridging collider, phase transition, and lattice studies

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Based on: [2302.11598], [2406.14633]

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Why Composite Higgs?

- **Hierarchy problem:** how the electroweak is stabilized under quantum corrections?

- **Is the Higgs boson an elementary particle?** might as well be a composite state, just like a pion!

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

- **Electroweak phase transition and CP violation:** depends on the shape of the scalar potential

Composite Higgs boson with partially composite top quark

Composite Higgs models

Main idea: UV theory without any elementary scalar

Couple the massless SM to a new strongly coupled gauge theory with fermionic matter
[Hypercolor] [Hyperquark]

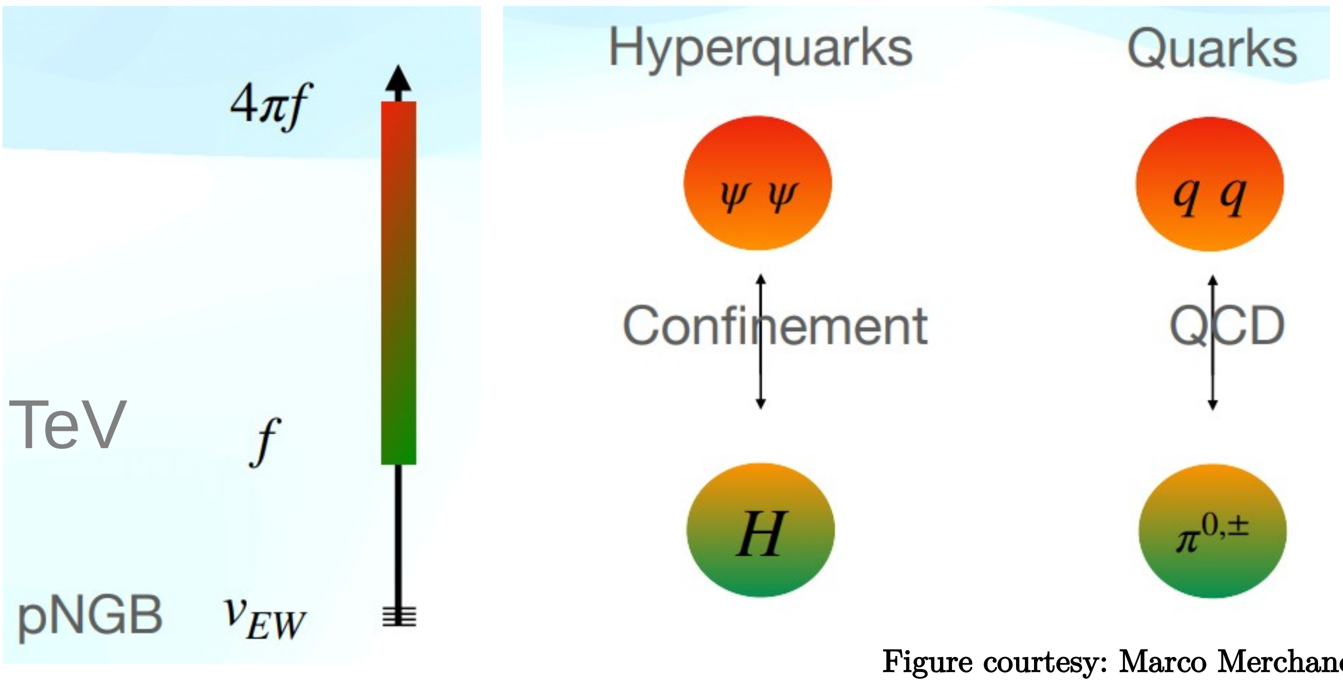
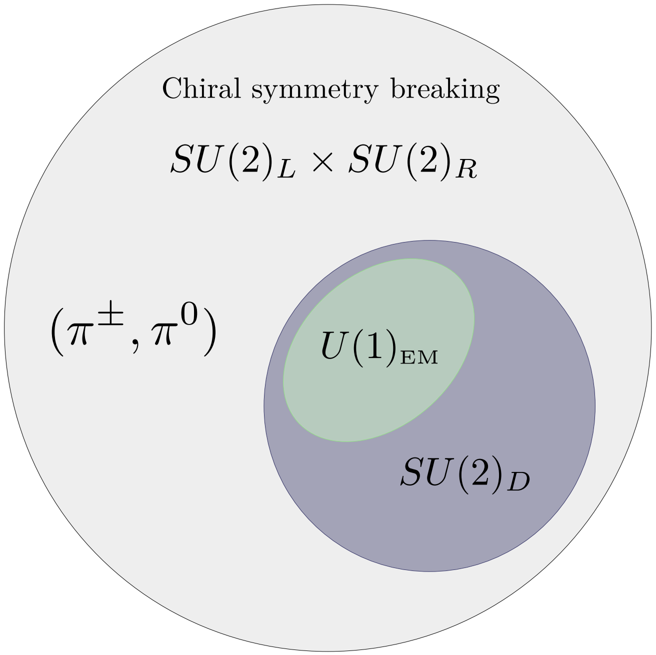


Figure courtesy: Marco Merchand

Dimensional transmutation creates large hierarchy of scales

Recap: QCD



- **Explicit breaking leads to pion potential**

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

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

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

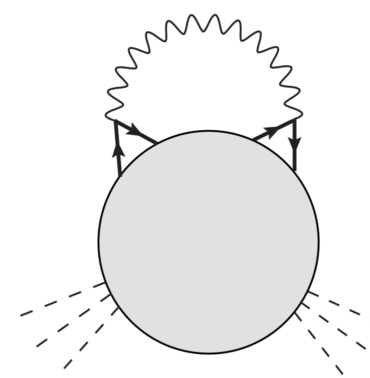
Gellmann-Oakes-Renner, 1968

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

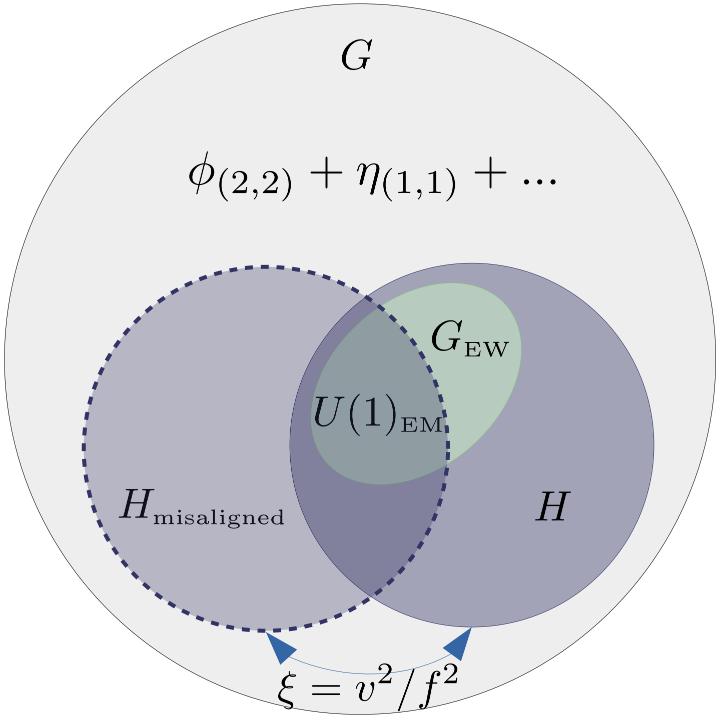
Mathur, Das, Guralnik, 1967

Electromagnetism remains unbroken

Witten, 1983

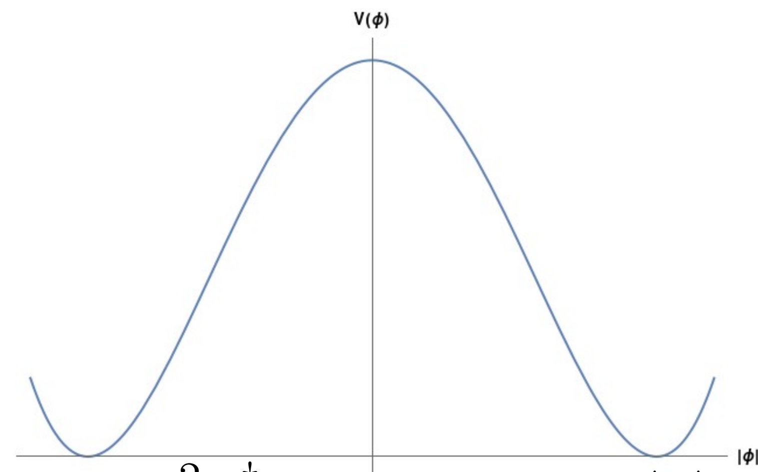


Composite Higgs vacuum



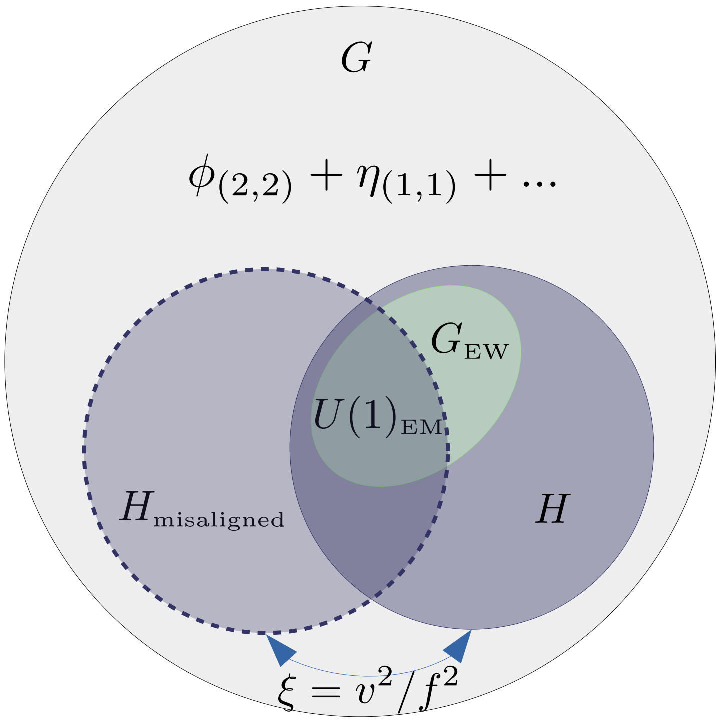
$$\frac{G}{H} \to \frac{\mathrm{SU}(4)}{\mathrm{Sp}(4)}, \frac{\mathrm{SU}(5)}{\mathrm{SO}(5)}, \frac{\mathrm{SU}(4)\times\mathrm{SU}(4)}{\mathrm{SU}(4)_{\mathrm{D}}}$$

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



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

Composite Higgs vacuum



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

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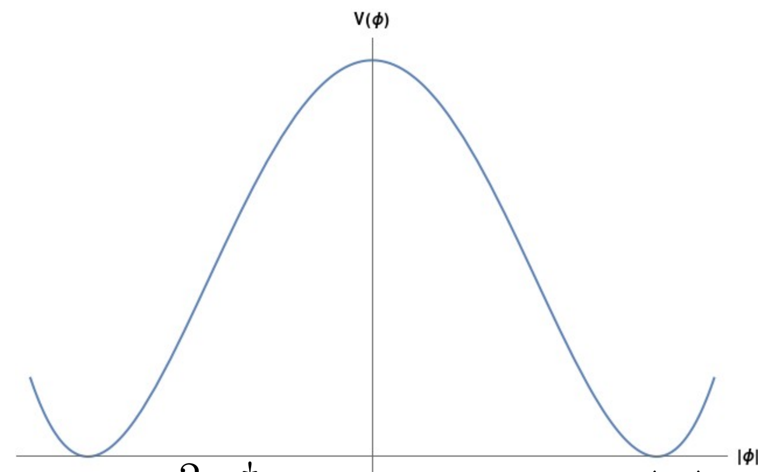


$$V_\phi \sim -\mu^2 \phi^\dagger \phi + \ldots \qquad \Longrightarrow \langle \phi \rangle \sim v$$

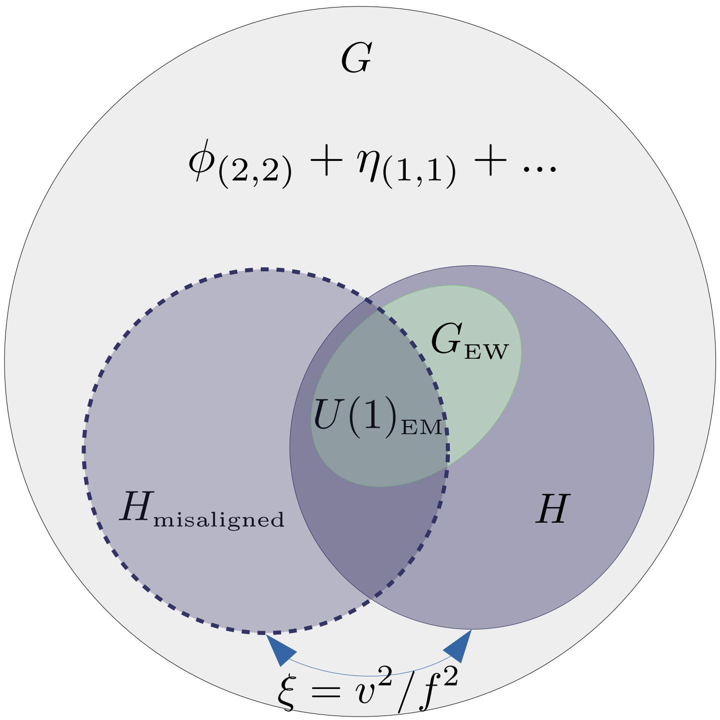
Analyze the potential around origin:

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

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

Tachyonic directions : **vacuum misalignment**

Vacuum misalignment

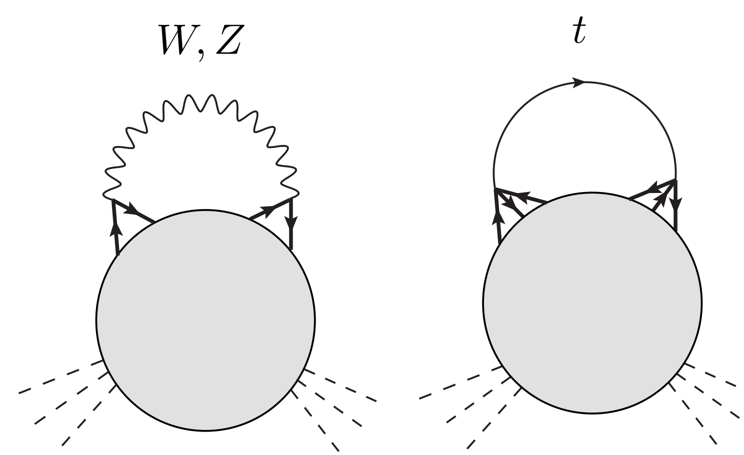


$$V = {}_{\Pi}\langle \text{vac}|\mathcal{H}|\text{vac}\rangle_{\Pi}$$
$$= V_{\rm mass} + V_{W,Z} + V_{\rm t}$$

Hyperquark mass | Gauge | Top quark partial compositeness

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

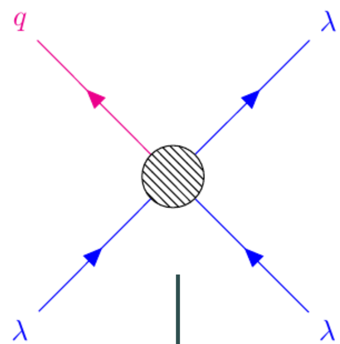
$$V_{\rm mass} + V_{W,Z} \sim +\mu^2\phi^\dagger\phi + \ldots$$



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

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

Partial compositeness

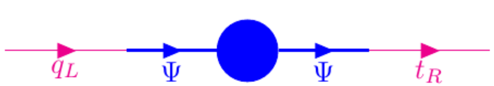


$$\sim \frac{c_{\mathrm{UV}}^2}{\Lambda_{\mathrm{UV}}^2} q\lambda^3 \qquad \Lambda_{\mathrm{UV}} \gg \Lambda_{\mathrm{HC}} \sim 4\pi f$$

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

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

EWSB



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

Requirements:

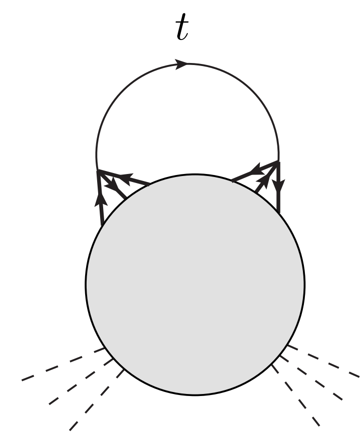
- **Nearly conformal dynamics above confinement scale**
- **Large anomalous dimension to reproduce top mass**
- **Lattice gauge theory studies required to compute the anomalous dimension**

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

- 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

$$\Psi \overset{G/H}{\to} \Psi_{R_1} + \Psi_{R_2} \qquad \Longrightarrow \; \kappa_1\, t\Psi_{R_1} + \kappa_2\, t\Psi_{R_2}$$



$$\mathcal{H}_{\rm PC} = -\frac{i}{2}\int d^4x \Delta^{\dot\alpha\alpha}(x)\, T\left\{\mathcal{K}^\dagger_R \Psi^R_\alpha(x)\Psi^\dagger_{Q\dot\alpha}(0)\mathcal{K}^Q + \text{h.c.}\right\}$$

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

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

SU(4)/Sp(4) coset: Higgs + CP odd singlet

Minimal Higgs potential hypothesis:
Potential is dominated by the IR contributions (Coleman-Weinberg)

Maximal symmetry: Fully calculable finite scalar potential

Effect of strong dynamics is captured by momentum dependent form factors

SU(4)/Sp(4) coset: Higgs + CP odd singlet

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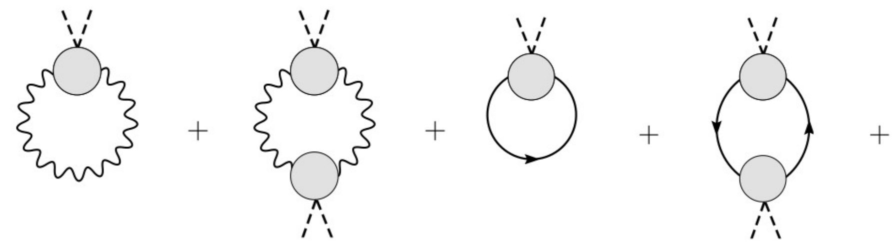
$$V_{1-\text{loop}}(h,\eta) = V_{\text{mass}} + V_g + V_t$$

$$V_{\text{mass}} = B f^3 \text{tr}\left[\mu_H U + U^\dagger \mu_H^\dagger\right]$$

- Tadpole for the singlet (CP violation)
- Numerically small but relevant for giving vev to the singlet



$$V_{\text{CW}} = \frac{N_{\text{eff}}}{2}\int \frac{d^4p}{(2\pi)^4}\log\left[1+\frac{m^2_{W,Z,t}(h,\eta)m_1^2 m_2^2}{p^2(p^2+m_1^2)(p^2+m_2^2)}\right]$$

Momentum dependence inside the integral is different from CW potential for elementary scalars

Full analytic computation: AB, M Merchand, I Nalecz JHEP 10 (2024) 106

Finite temperature potential

Imaginary time formalism: $\int dp^0 d^3p\; f(p^2) \to 2\pi T \sum_{n=-\infty}^{\infty} \int d^3p\; f(\omega_n^2 + |\vec{p}|^2)$

$$V_{\text{1-loop}} = V_{\text{CW}}^{(T=0)}(\tilde{m}_i) + N_{\text{eff}} \frac{T^4}{2\pi^2} \sum_{i=1}^{3} J_B\left(\frac{\tilde{m}_i}{T}\right)$$

$$V_{\text{CW}}^{(T=0)}(\tilde{m}_i) \equiv \frac{N_{\text{eff}}}{2} \int \frac{d^3p}{(2\pi)^3} \sum_{i=1}^{3} \tilde{E}_i = \frac{N_{\text{eff}}}{32\pi^2} \sum_{i=1}^{3} \tilde{m}_i^4 \log\left(\frac{\tilde{m}_i}{\mu}\right)$$

Zero temperature part nicely separates even in the presence of form factors

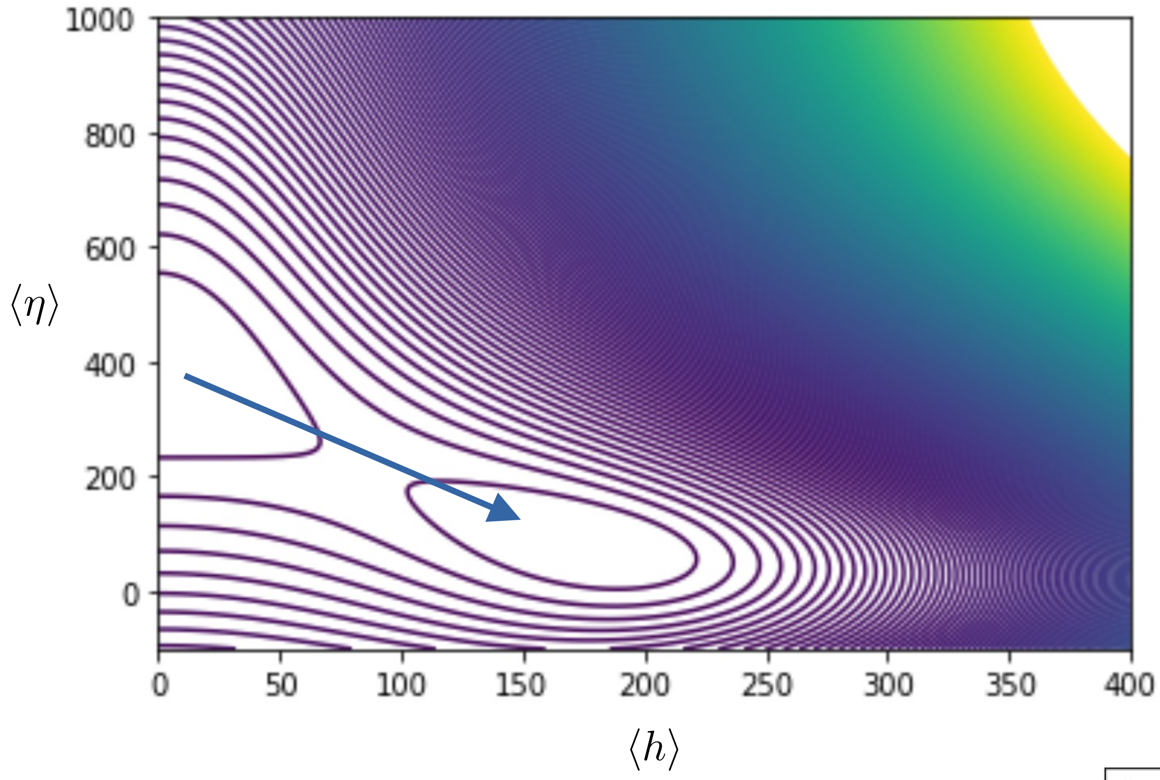
Fully calculable with maximal symmetry

$$J_B(x) \equiv \int_0^\infty dy\, y^2 \log\left[1 - e^{-\sqrt{y^2+x^2}}\right]$$

Contributions from W,Z,t dominates

Resonance contributions are exponentially suppressed for $T_n \sim 100$ GeV

Phase transition and Gravitational wave

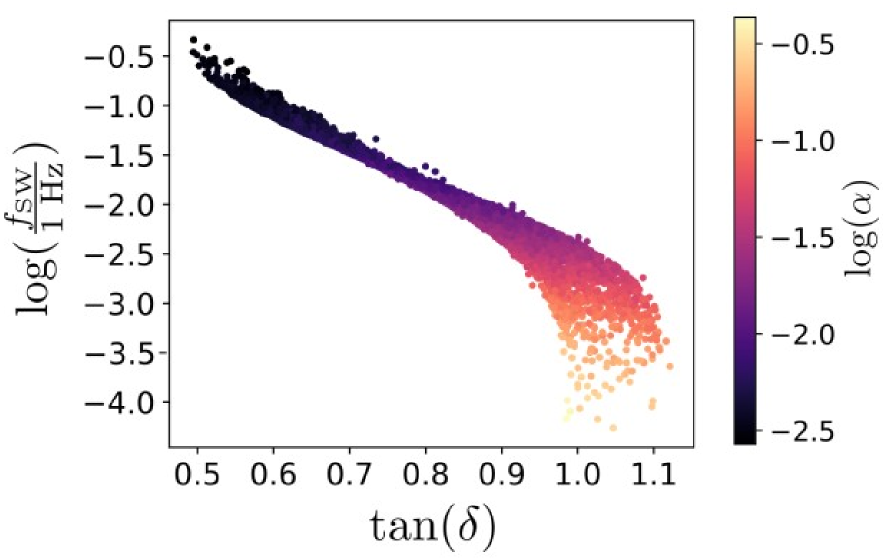


Tunneling from false vacuum to true EW vacuum by one step transition

Nucleation temperature: $T_n \sim v_{EW}$

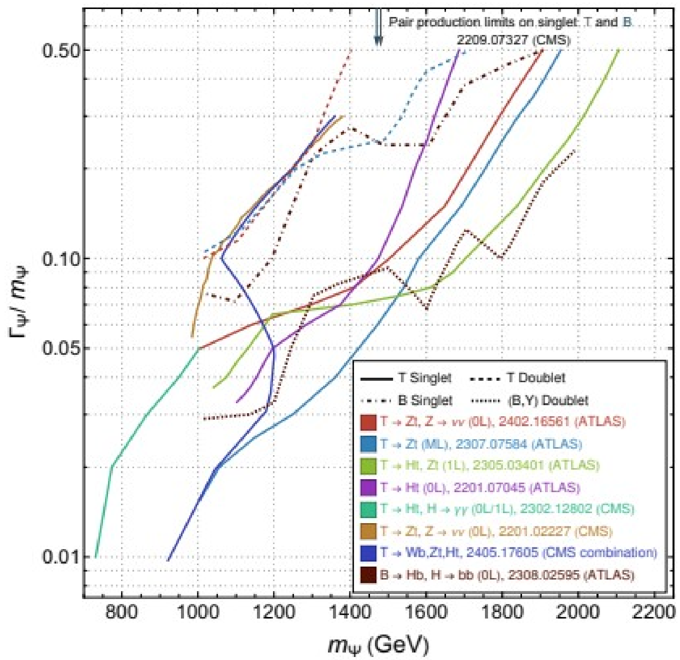
In presence of CP violation FOPT is viable even with IR contributions to the pNGB potential

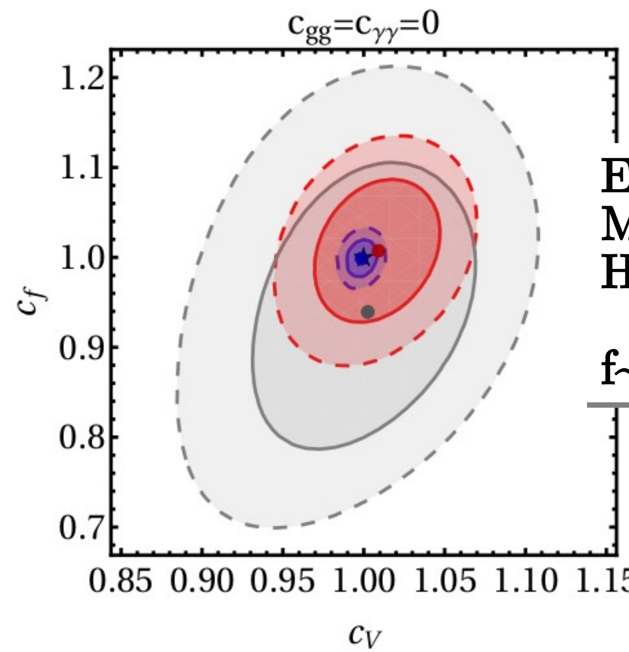
Latent heat of FOPT and the peak frequency of the GWs depend on the amount of CP violation



AB, M Merchand, I Nalecz JHEP 10 (2024) 106

Collider probes and constraints



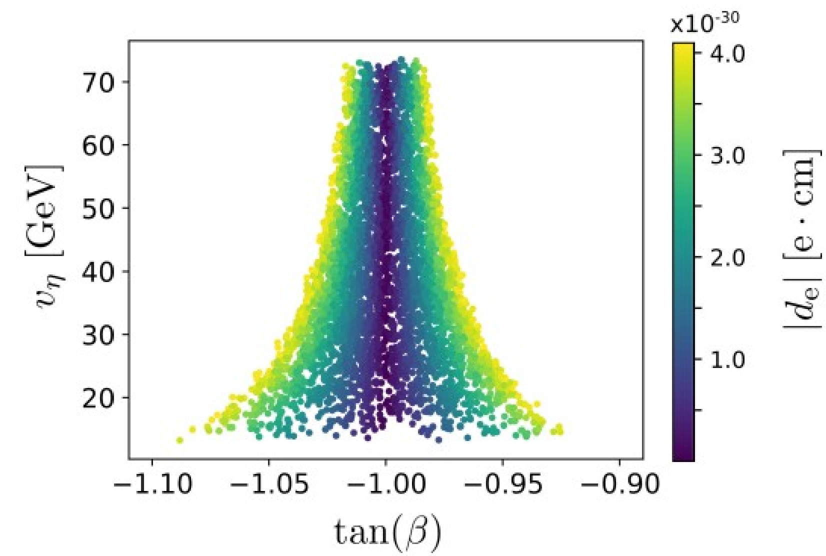


EWPO +
Modification of
Higgs couplings

f~ 1 TeV

Search for new resonances
Top-partners, spin-1 resonances,
pNGBs @LHC

M~ 1.5 TeV



CP violation: electron EDM measurements

$$|d_e| \leq 4.1 \times 10^{-30} e\ \mathrm{cm}$$

Bounds on singlet vev

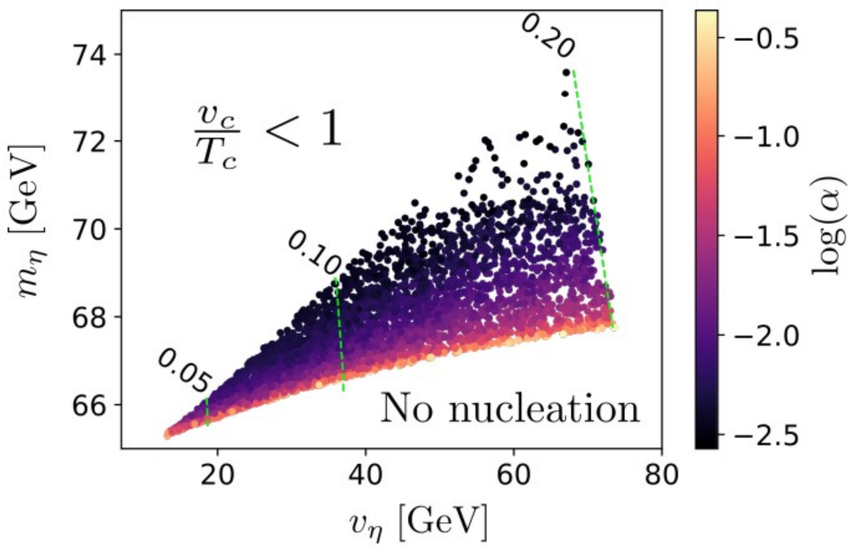
Gravitational waves @LISA

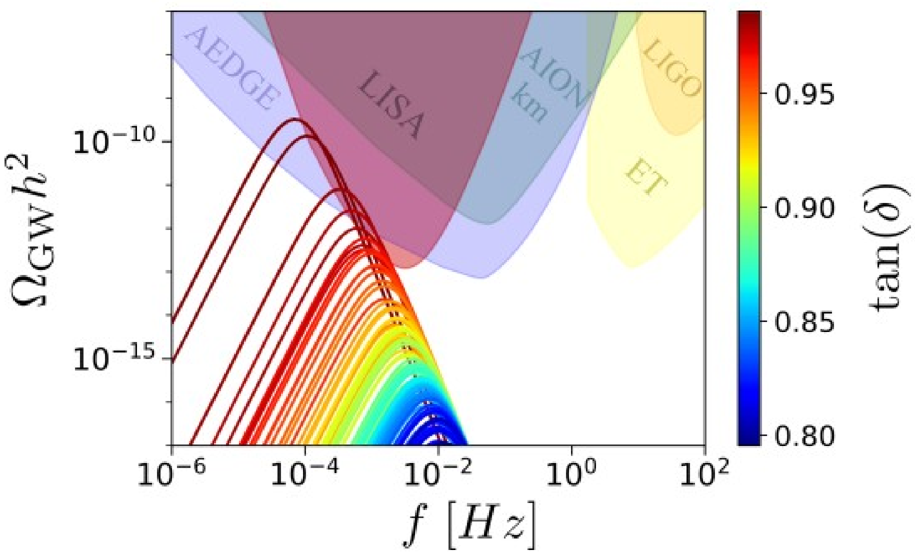
Collider + FOPT selects a narrow region of parameters

$m_h/2 <$ Light singlet $< m_h$,

small mixing with Higgs
(constrained from invisible BR of Higgs)

Explicit CP violation
(partly constrained by eEDM)





CP violating phase from hyperquark masses

AB, M Merchand, I Nalecz JHEP 10 (2024) 106

Major References

- Pioneering works:
  - Composite pNGB Higgs: D B Kaplan, H Georgi, Phys. Lett. B 136 (1984) 183.
  - Partial compositeness: D B Kaplan, Nucl. Phys. B 365 (1991) 259.

- Modern composite Higgs models:
  - 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 … …

- Our contributions:
  - [1703.08011], [1712.07494], [2006.01164], [2105.01093], [2202.00037], [2203.07270], [2302.11598], [2311.17877], [2406.09193], [2406.14633]
  - In collaboration with G Bhattacharyya, S Dasgupta, D B Franzosi, G Ferretti, N Kumar, L Panizzi, T S Ray, V Ellajosyula, E B Kuutmann, R Enberg, W Porod, G Cacciapaglia, A Deandrea, B Fuks and others

Summary

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

- **Lattice gauge theory studies** required for more information on the anomalous dimensions of partial compositeness operators

- Major predictions involve existence of **vector-like quarks, spin-1 resonances and light pNGBs**, all accessible **@LHC**

- **First order phase transition** at the EW scale is possible in presence of **explicit CP violation**, resulting **GWs @LISA** sensitivity range provide complimentary probe

Thank you!

Backup

UV theory of partial compositeness

Main idea is to start with a model without any elementary scalar

Couple the massless SM with a new strongly coupled gauge theory with fermionic matter
[Hypercolor] [Hyperquark]

Fields	G_{HC}	G_{SM}
$\lambda \equiv (\psi, \chi, \ldots)$	R_1	R_2
$f \equiv (q, l)$		R_{SM}

$$\mathcal{L}_{UV} \supset -\frac{1}{4}\sum_{G_{HC}, G_{SM}} F_{\mu\nu}^2 + i\sum_{\lambda, f}\bar{\psi}\not{D}\psi - \sum_{\lambda} m_\psi \bar{\psi}\psi$$

vectors dim-6	F^3	~~F^2G~~	~~FG^2~~	G^3		
fermions dim-6	f^4	~~$f^3\lambda$~~	$f^2\lambda^2$	$f\lambda^3$	λ^4	
mixed dim-5	~~fFf~~	~~λFf~~	~~fGf~~	$\lambda F\lambda$	λGf	$\lambda G\lambda$
mixed dim-6	$fFDf$	~~λFDf~~	~~$fGDf$~~	$\lambda FD\lambda$	λGDf	$\lambda GD\lambda$

We will soon talk about the global symmetries of the strong sector

Comparison with QCD

- **The hypercolor theory confines at** $\Lambda_{\rm HC} \sim 4\pi f \sim 10~\rm TeV$
- **Higgs boson appears as a pNGB with decay constant** $f \sim 1~\rm TeV$

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

Properties	QCD	Composite Higgs
Gauge group	$\mathrm{SU}(3)_c$	Hypercolor, SU(N) / Sp(N) / SO(N)
Fundamental dof	Quarks, Gluons	Hyperquarks, Hypergluons
Global symmetry	$\frac{\mathrm{SU(3)_L \times SU(3)_R}}{\mathrm{SU(3)_D}}$	$\frac{\mathrm{SU(N)}}{\mathrm{SO(N)}}, \frac{\mathrm{SU(N)}}{\mathrm{Sp(N)}}, \frac{\mathrm{SU(N)\times SU(N)}}{\mathrm{SU(N)_D}}$
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

Global symmetries

- Wish List:
  - Anomaly free hyperquark content, leading to asymptotically free gauge theory
  - Global symmetry breaking pattern: $G_F \to H_F \supset G_{\rm cust} \times SU(3)_c \supset G_{\rm SM}$
  - At least one Higgs doublet among the pNGBs, requires color neutral hyperquarks ψ
  - VLQs, which can mix with SM quarks: partial compositeness, requires colored hyperquarks χ

	$\psi \in$ R	$\psi \in$ PR	$\psi, \tilde{\psi} \in$ C
$\chi \in$ R	$\frac{SU(5)}{SO(5)} \times \frac{SU(6)}{SO(6)} \times U(1)_u$	$\frac{SU(4)}{Sp(4)} \times \frac{SU(6)}{SO(6)} \times U(1)_u$	$\frac{SU(4)\times SU(4)'}{SU(4)_D} \times \frac{SU(6)}{SO(6)} \times U(1)_u$
$\chi \in$ PR	$\frac{SU(5)}{SO(5)} \times \frac{SU(6)}{Sp(6)} \times U(1)_u$	~~$\frac{SU(4)}{Sp(4)} \times \frac{SU(6)}{Sp(6)} \times U(1)_u$~~	~~$\frac{SU(4)\times SU(4)'}{SU(4)_D} \times \frac{SU(6)}{Sp(6)} \times U(1)_u$~~
$\chi, \tilde{\chi} \in$ C	$\frac{SU(5)}{SO(5)} \times \frac{SU(3)\times SU(3)'}{SU(3)_D} \times U(1)_u$	~~$\frac{SU(4)}{Sp(4)} \times \frac{SU(3)\times SU(3)'}{SU(3)_D} \times U(1)_u$~~	$\frac{SU(4)\times SU(4)'}{SU(4)_D} \times \frac{SU(3)\times SU(3)'}{SU(3)_D} \times U(1)_u$

EW pNGB content:

$\mathbf{A}_2$ of $Sp(4) \to (1,1) + (2,2)$

$\mathbf{S}_2$ of $SO(5) \to (1,1) + (2,2) + (3,3)$

$\mathbf{Ad}$ of $SU(4)_D \to (1,1) + 2.(2,2) + (3,1) + (1,3)$

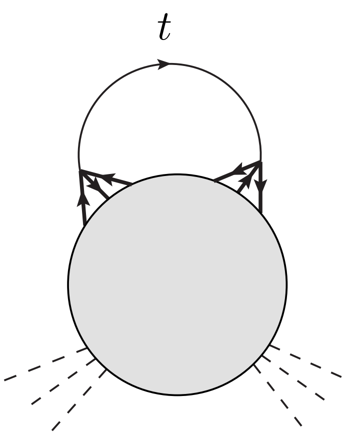
Important prediction:

Two global U(1) symmetries, out of which one combination is non-anomalous

Existence of an ALP ~ few GeV

Vacuum misalignment *via* 4-Fermi operators

$$\Psi \overset{G/H}{\to} \Psi_{R_1} + \Psi_{R_2} \quad \Longrightarrow \kappa_1 \, t\Psi_{R_1} + \kappa_2 \, t\Psi_{R_2}$$

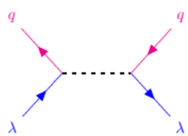


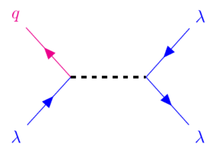
$$\mathcal{H}_{\rm PC} = -\frac{i}{2}\int d^4x \Delta^{\dot\alpha\alpha}(x)\, T\left\{\mathcal{K}^\dagger_R \Psi^R_\alpha(x)\Psi^\dagger_{Q\dot\alpha}(0)\mathcal{K}^Q + \text{h.c.}\right\}$$

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

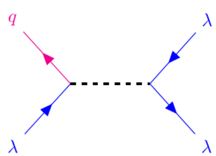
$SU(N)$	$\to$	$SO(N)$	
$\mathbf{Ad}$		$\mathbf{Ad} + \mathbf{S}_2$	$\text{tr}(\mathcal{P}U\mathcal{P}^*U^*)$
$\mathbf{S}_2$		$\mathbf{1} + \mathbf{S}_2$	$\text{tr}(\mathcal{P}U^*)\text{tr}(\mathcal{P}^*U)$
$SU(2N)$	$\to$	$Sp(2N)$	
$\mathbf{Ad}$		$\mathbf{Ad} + \mathbf{A}_2$	$\text{tr}(\mathcal{P}U\mathcal{P}^*U^*)$
$\mathbf{A}_2$		$\mathbf{1} + \mathbf{A}_2$	$\text{tr}(\mathcal{P}U^*)\text{tr}(\mathcal{P}^*U)$
$SU(N)\times SU(N)$	$\to$	$SU(N)$	
$(\mathbf{F},\mathbf{F})$		$\mathbf{A}_2 + \mathbf{S}_2$	$\text{tr}(U\mathcal{P}^TU^*\mathcal{P}^\dagger)$
$(\mathbf{F},\overline{\mathbf{F}})$		$\mathbf{1} + \mathbf{Ad}$	$\text{tr}(\mathcal{P}U^\dagger)\text{tr}(\mathcal{P}^\dagger U)$

Vector-like quark spectrum

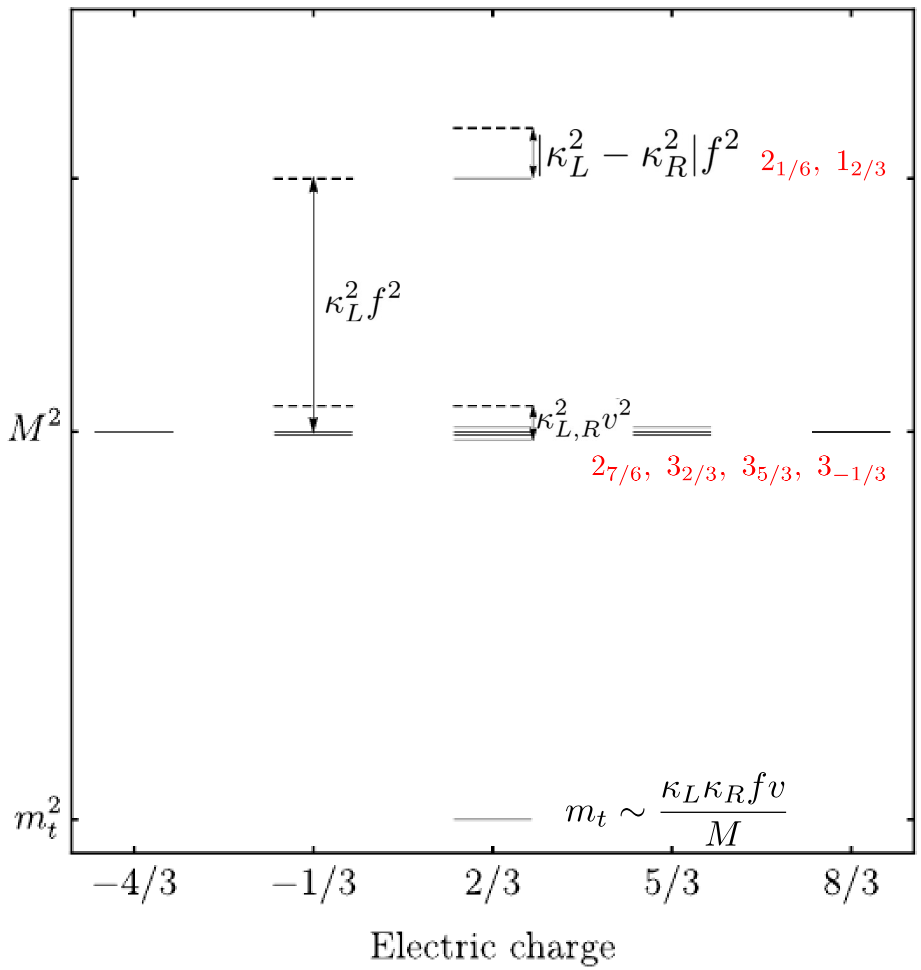




$$\begin{pmatrix} \bar{u}_L^1 \\ \bar{u}_L^2 \\ \bar{u}_L^3 \\ \bar{T}_L^1 \\ \vdots \\ \bar{T}_L^n \end{pmatrix}^T \left(\begin{array}{c|c} y_{3\times 3}^{ij} v & \kappa_L^i f \mathcal{F}_L(\frac{v}{f}) \\ \hline \kappa_R^j f \mathcal{F}_R(\frac{v}{f}) & M \mathbb{1}_n \end{array} \right) \begin{pmatrix}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



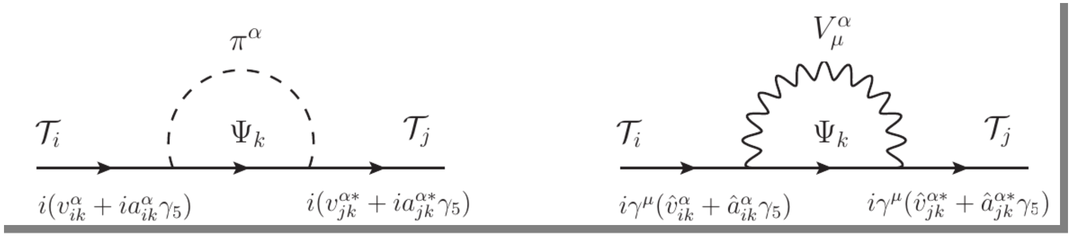
$$m_{1,2} \sim yv \qquad m_3 \sim \frac{\kappa_L \kappa_R f v}{M} + yv \gg yv$$



- 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

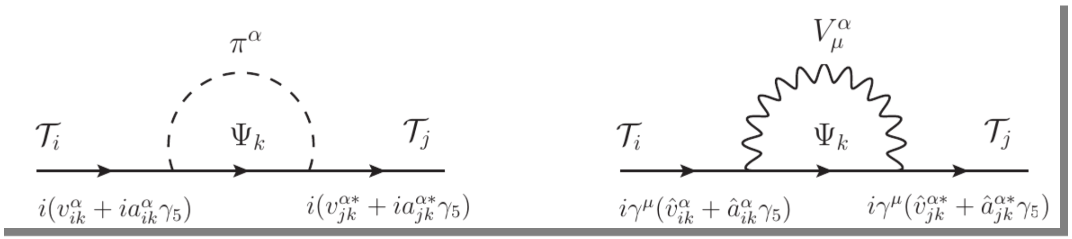
Overlapping resonance states

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

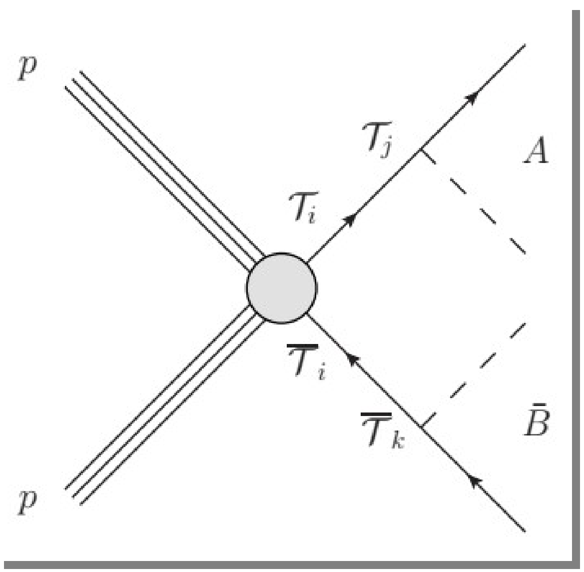


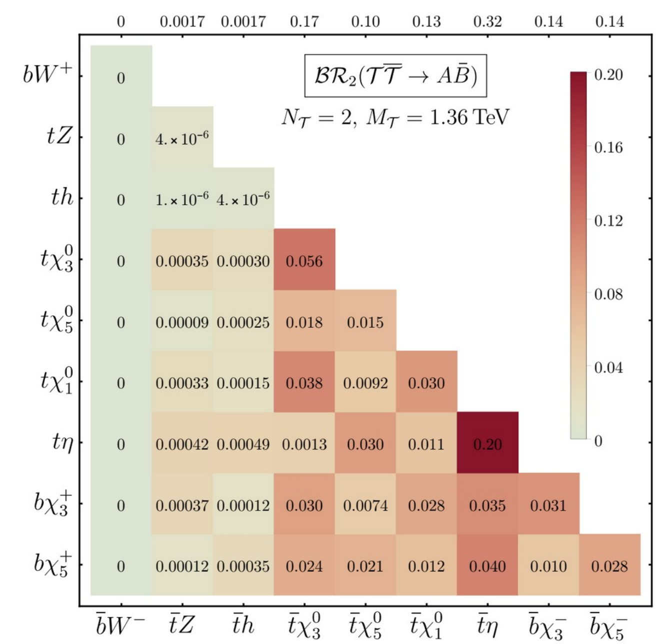
Overlapping resonance states

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



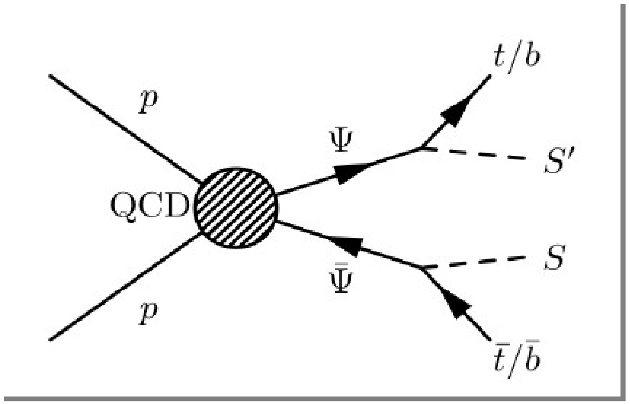
- Quantum interference leads to correlations between final states in a pair production process

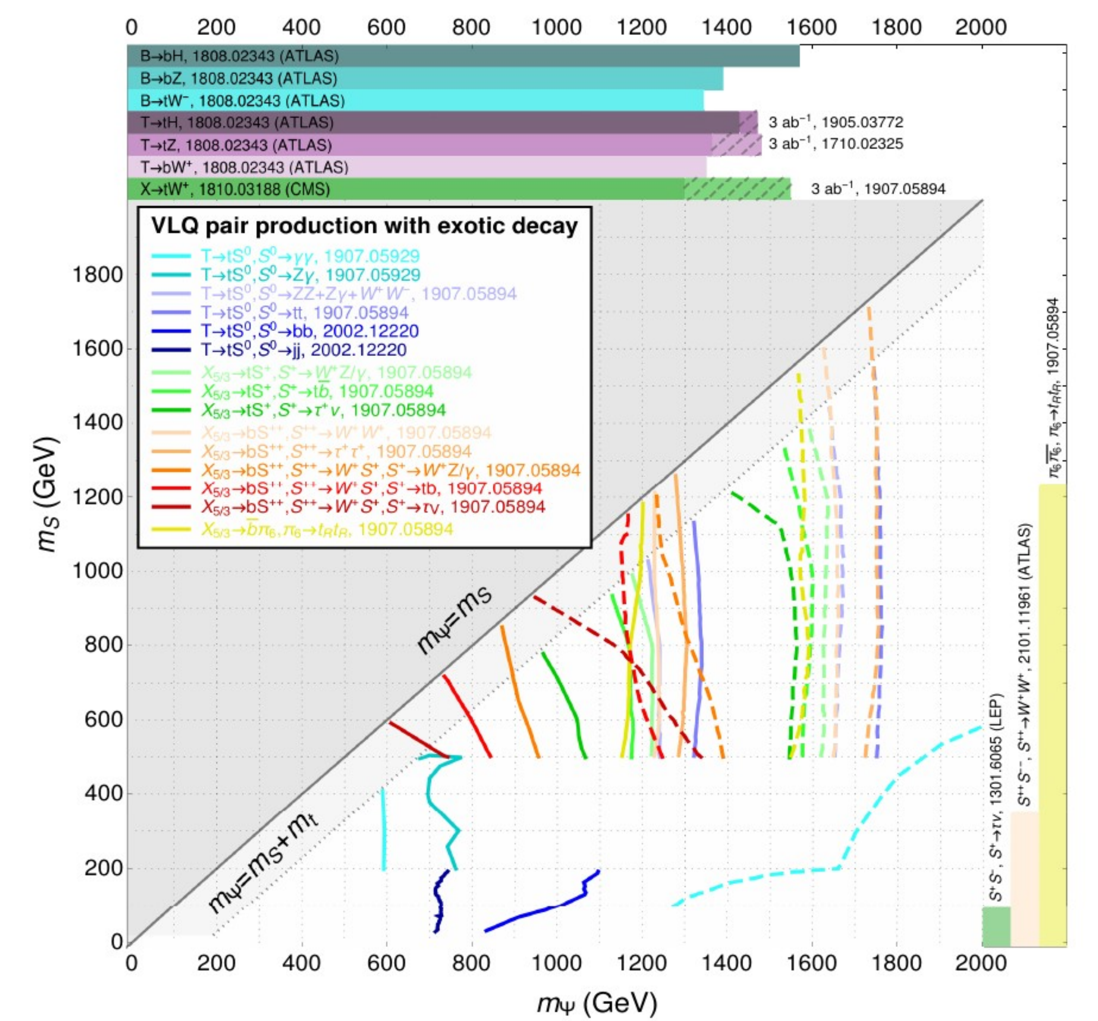




AB, D B Franzosi, G Ferretti, JHEP 03 (2022) 200

Vector-like quarks @LHC





Limitations/ Rooms for improvement:

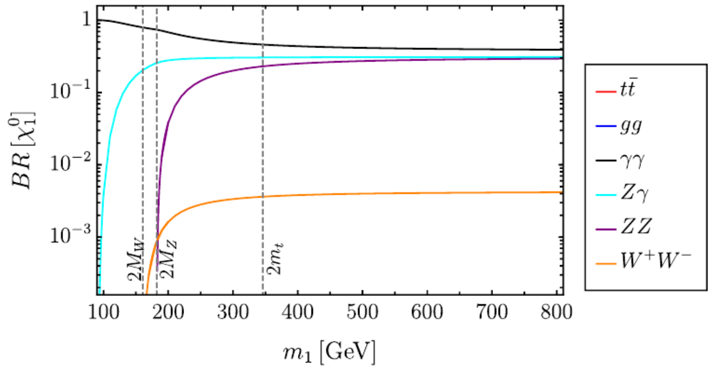
- Simplified model framework
- Interacting only with SM states
- 100% BR to specific SM channels
- Narrow width approximation

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

BSM decays of VLQs

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

Ongoing ATLAS search in diphoton final states



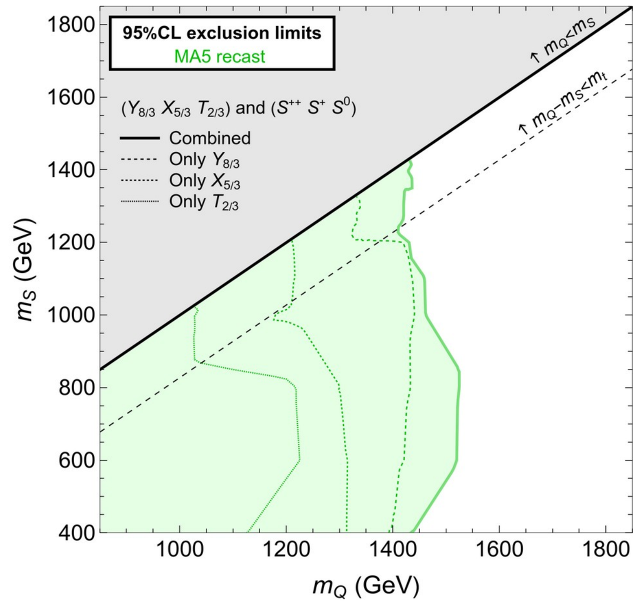
Benchmark coset: SU(5)/SO(5)

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

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

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

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



AB, V Ellajosyula, L Panizzi, [2311.17877]