MODELLING VECTOR-LIKE QUARKS IN PARTIAL COMPOSITENESS FRAMEWORK

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Vector-like quarks: defining features

A fermion is called vector-like if its left-handed and right-handed chiralities transform identically under a gauge group

e.g. SM quarks are vector-like under QCD and EM, but chiral under the electroweak group

Example: Charged current $$\mathcal{L} = \frac{g}{\sqrt{2}} j^\mu W_\mu^+ + \text{h.c.}$$

Chiral quarks:

$$j^\mu = j_L^\mu + j_R^\mu = \bar{f}_L \gamma^\mu f_L' = \bar{f} \gamma^\mu (1 - \gamma_5) f'$$ **V-A structure**

Vector-like quarks:

$$j^\mu = j_L^\mu + j_R^\mu = \bar{f}_L \gamma^\mu f_L' + \bar{f}_R \gamma^\mu f_R' = \bar{f} \gamma^\mu f'$$ **V structure**

Distinguishing Features:

1. **Gauge invariant Dirac mass term exists without Higgs insertion**
2. **Axial anomalies are automatically absent**

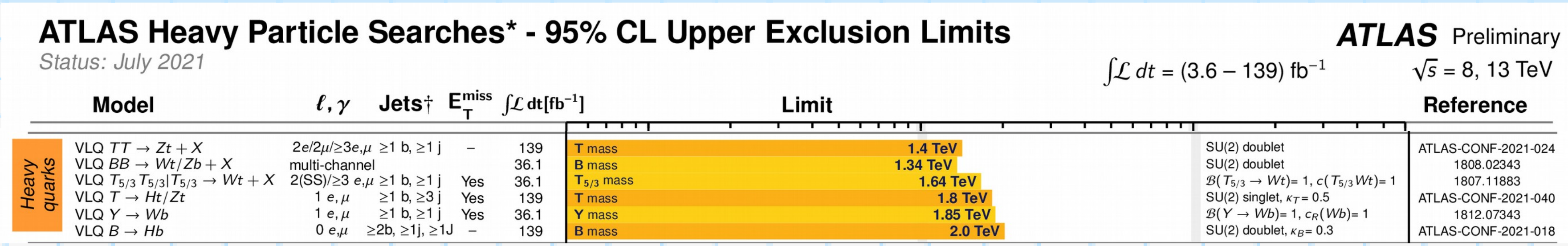
Vector-like quark representations

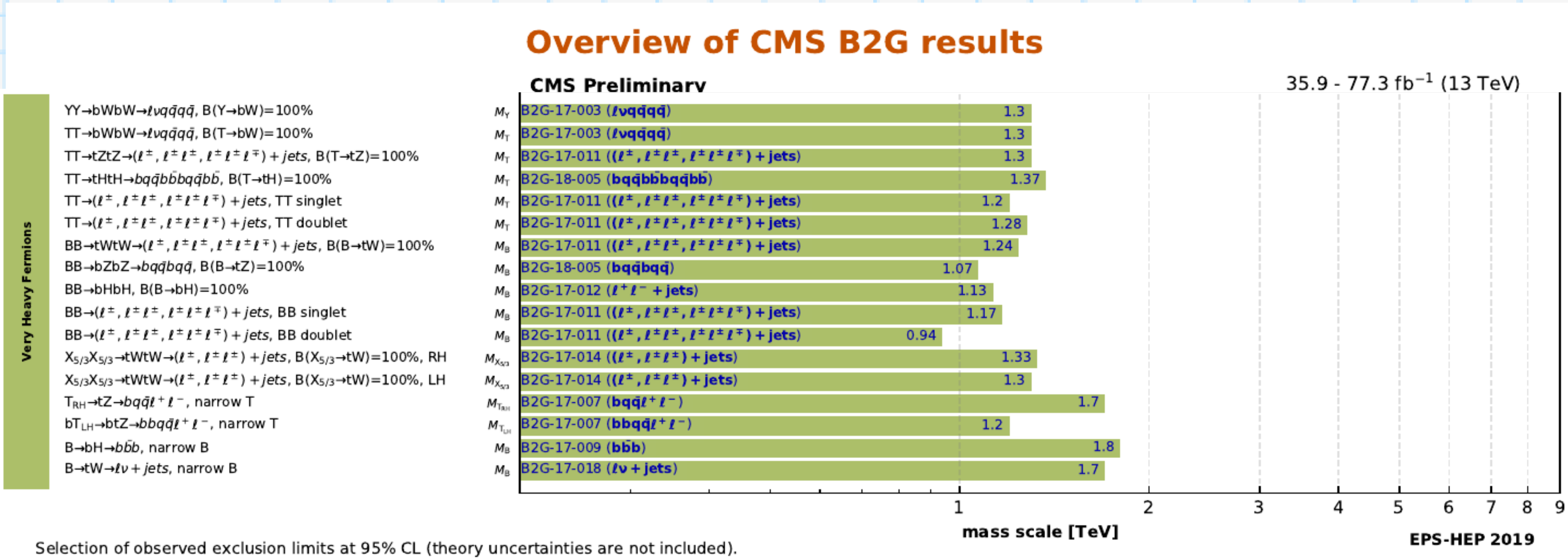
$\mathrm{SU(2)_L \times U(1)_Y}$ multiplets			
$\mathbf{2}_{\frac{1}{6}}: \begin{pmatrix} T_{\frac{2}{3}} \\ B_{-\frac{1}{3}} \end{pmatrix}$	$\mathbf{2}_{\frac{7}{6}}: \begin{pmatrix} X_{\frac{5}{3}} \\ X_{\frac{2}{3}} \end{pmatrix}$		
$\mathbf{3}_{\frac{2}{3}}: \begin{pmatrix} Y_{\frac{5}{3}} \\ Y_{\frac{2}{3}} \\ Y_{-\frac{1}{3}} \end{pmatrix}$	$\mathbf{1}_{\frac{5}{3}}: \tilde{X}_{\frac{5}{3}}$	$\mathbf{1}_{\frac{2}{3}}: \tilde{T}_{\frac{2}{3}}$	$\mathbf{1}_{-\frac{1}{3}}: \tilde{B}_{-\frac{1}{3}}$
$\mathbf{3}_{\frac{2}{3}}: \begin{pmatrix} Y_{\frac{5}{3}} \\ Y_{\frac{2}{3}} \\ Y_{-\frac{1}{3}} \end{pmatrix}$	$\mathbf{3}_{\frac{5}{3}}: \begin{pmatrix} U_{\frac{8}{3}} \\ U_{\frac{5}{3}} \\ U_{\frac{2}{3}} \end{pmatrix}$	$\mathbf{3}_{-\frac{1}{3}}: \begin{pmatrix} V_{\frac{2}{3}} \\ V_{-\frac{1}{3}} \\ V_{-\frac{4}{3}} \end{pmatrix}$	

Vector-like quarks in New Physics models:

1. Extra-dimensions: KK excitations
2. Composite Higgs models: excited resonances of the bound states
3. Little Higgs models: partners of SM fermions
4. Non-minimal SUSY extensions: raising Higgs mass without affecting EWPT

Status of VLQ search @LHC





Caveats:

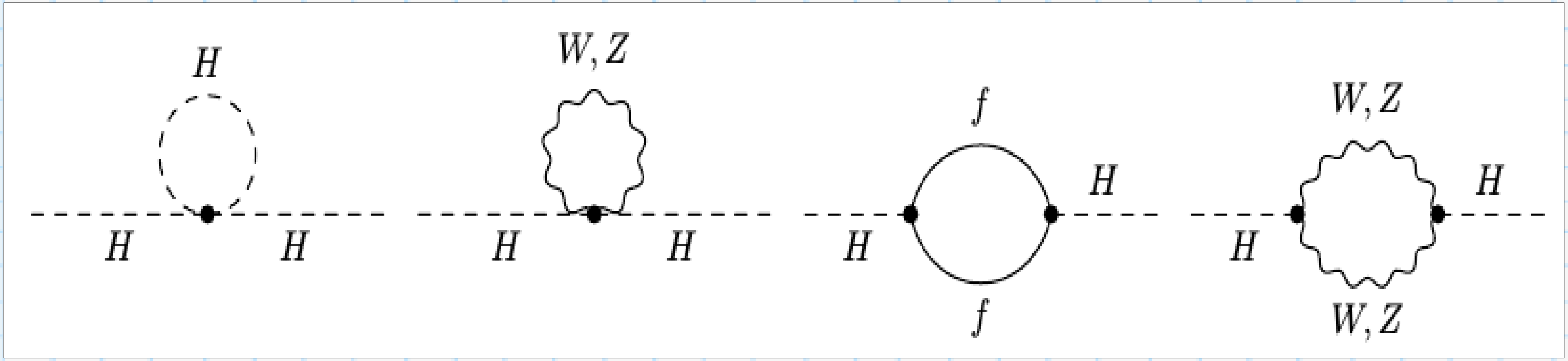
- Simplified model framework
- SM extended with only one representation of VLQs
- Interacting only with SM states
- 100% BR to specific SM channels
- Narrow width approximation

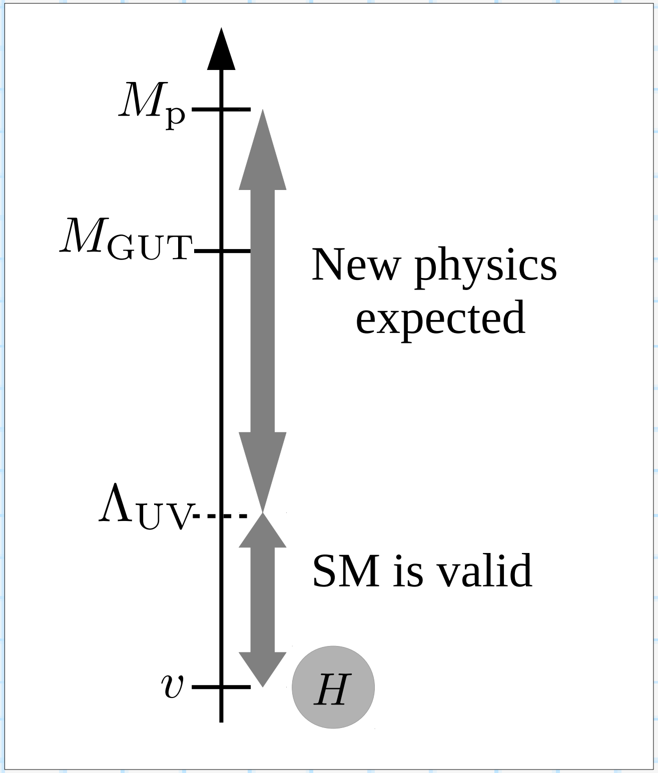
Outline of the talk

- Composite Higgs models
  - ➔ Motivation
  - ➔ Basic construction
  - ➔ Partial compositeness
- Low energy theory of VLQs
  - ➔ Low energy Lagrangian
  - ➔ Spectrum of vector-like partners
  - ➔ Possible signatures at colldier
- Summary

Composite Higgs Models

Hierarchy problem





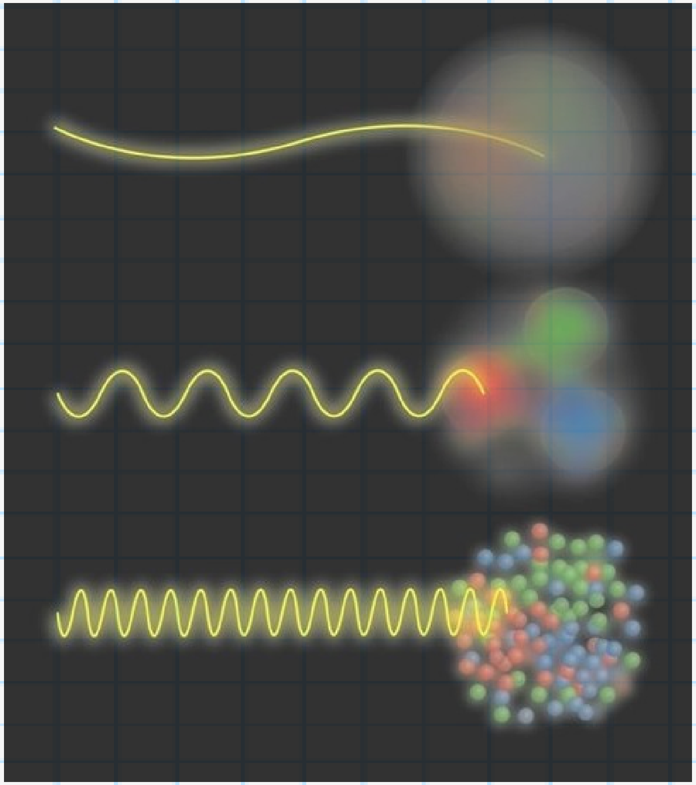
$$\delta m_h^2 \simeq \frac{\lambda_i}{16\pi^2}\Lambda_{\mathrm{UV}}^2$$

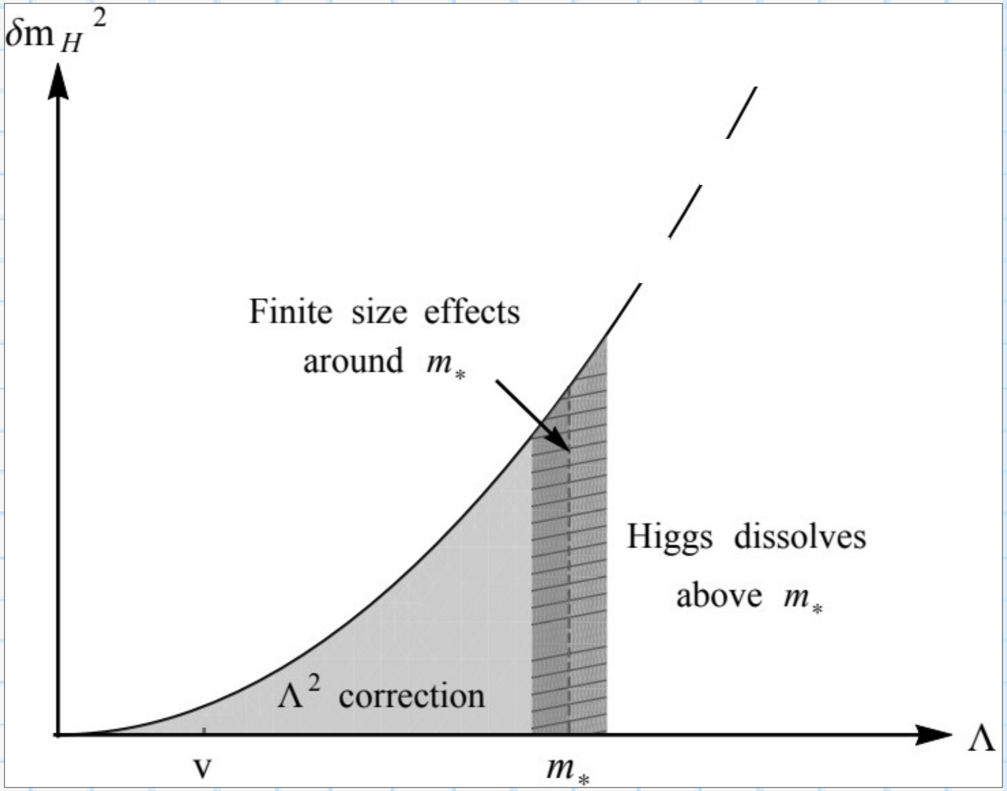
"Technically unnatural"

Unlike fermions or gauge bosons
No enhanced symmetry protection

Composite pNGB Higgs

- Higgs is a composite bound state of a strongly interacting sector
- Higgs emerges as a pseudo Nambu-Goldstone boson (pNGB)





Basic construction

Properties	QCD	Composite Higgs
Confining gauge group	$\mathrm{SU}(3)_\mathrm{c}$	Hypercolor $\mathrm{SU(n)},\ \mathrm{Sp(n)},\ \mathrm{SO(n)}$
Fundamental dof	Quarks & Gluons	Hyperquarks & Hypergluons
Global symmetry	$\mathrm{SU}(2)_\mathrm{L} \times \mathrm{SU}(2)_\mathrm{R}/\mathrm{SU}(2)_\mathrm{D}$	G/H
pNGBS $\langle\bar{\psi}\psi\rangle$	Pions	Higgs + BSM pNGBs
$\langle\bar{\psi}\gamma^\mu\psi\rangle$	Rho-mesons	Spin-1 vector resonances
$\langle\bar{\psi}\psi\psi\rangle$	Baryons	Top-partners
Vacuum misalignment	No	Yes (triggers EWSB)

[Barnard et al. 1311.6562], [Ferretti et al. 1312.5330, 1404.7137]

Types of cosets arising from 4D strongly coupled theory with fermionic matter in the UV

$(\psi_\alpha, \tilde{\psi}_\alpha)$ Complex	$\langle \tilde{\psi}\psi \rangle \neq 0 \Rightarrow SU(n) \times SU(n)'/SU(n)_D$
ψ_α Pseudoreal	$\langle \psi\psi \rangle \neq 0 \Rightarrow SU(n)/Sp(n)$
ψ_α Real	$\langle \psi\psi \rangle \neq 0 \Rightarrow SU(n)/SO(n)$

Three minimal cosets (Higgs doublet + custodial symmetry):

$4\ (\psi_\alpha, \tilde{\psi}_\alpha)$ Complex	$SU(4) \times SU(4)'/SU(4)_D$
$4\ \psi_\alpha$ Pseudoreal	$SU(4)/Sp(4)$
$5\ \psi_\alpha$ Real	$SU(5)/SO(5)$

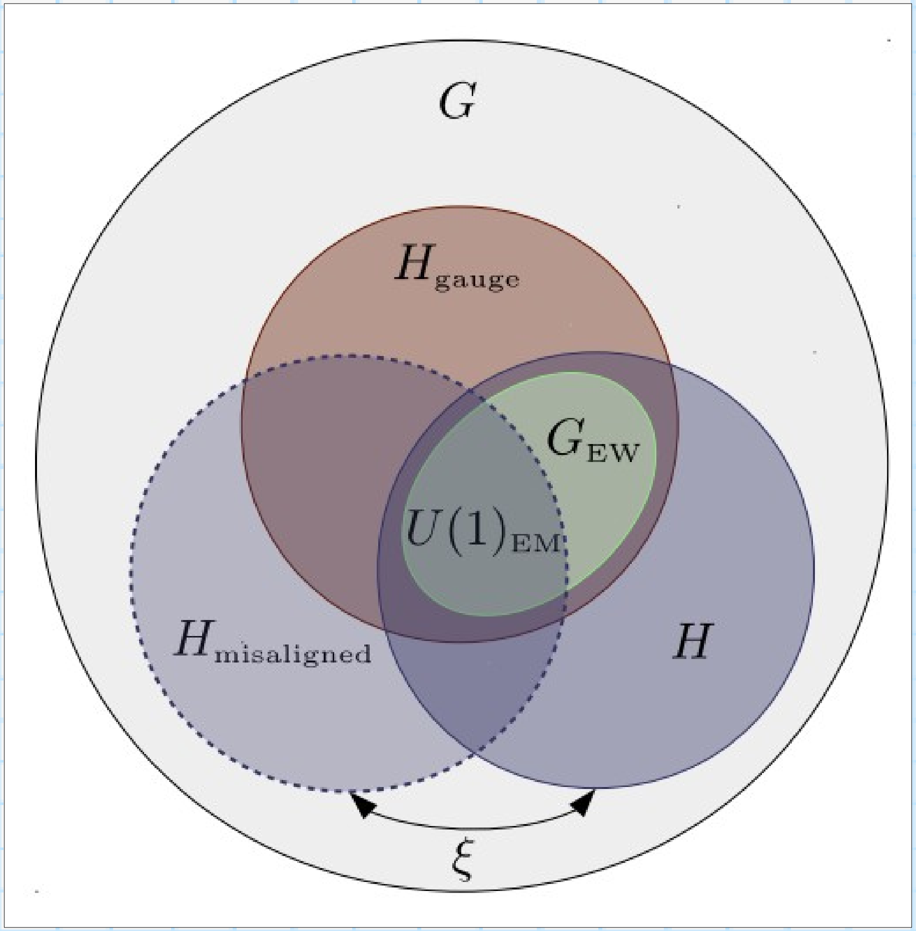
- Other cosets: SO(n)/SO(n-1), SO(n)/SO(m)x SO(n-m)
  These can be realized in 5D holographic composite Higgs models

  Popular example is MCHM with SO(5)/SO(4) coset

[Agashe et al. hep-ph/0412089]

Vacuum misalignment

- Explicit breaking of global symmetry leads to 1-loop Coleman Weinberg potential for the pNGBs
- Hyperquark and gauge contributions to the potential can not misalign the vacuum
- Contribution from top quark is essential to trigger EWSB

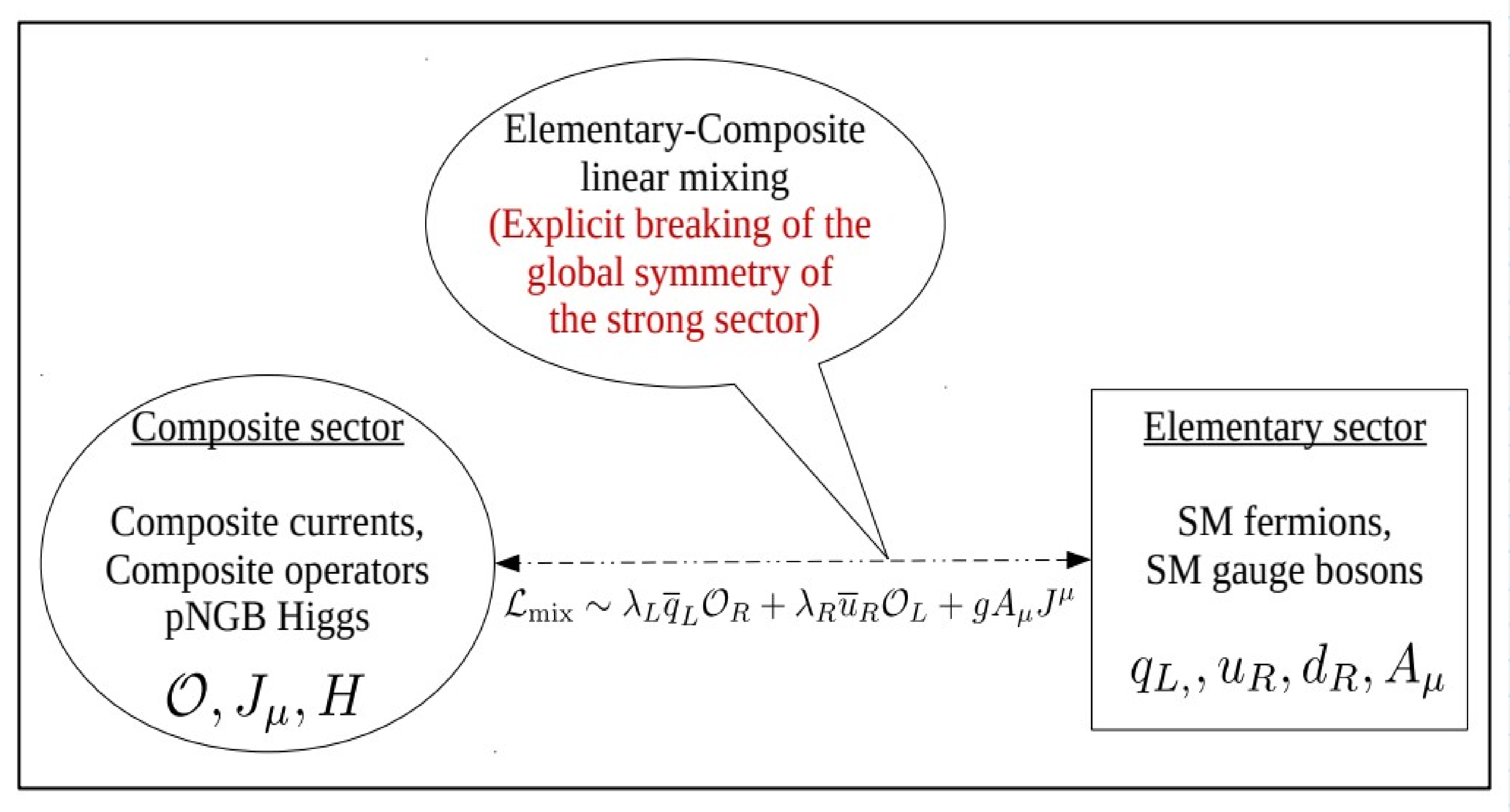


$$\xi = \frac{v^2}{f^2} \ll 1$$

$\xi \to 0$ $\xi \to 1$

SM ← Composite Higgs → Technicolor

Partial compositeness paradigm



Physical states are linear combination of elementary and composite states

$$|\mathrm{SM}\rangle = \cos\phi|\mathrm{elem}\rangle + \sin\phi|\mathrm{comp}\rangle$$

Top-partners

$$\mathcal{L}_{\rm mix} \simeq \frac{\lambda_L}{\Lambda_{\rm UV}^{d_L-5/2}}\bar{q}_L\mathcal{O}_R + \frac{\lambda_R}{\Lambda_{\rm UV}^{d_R-5/2}}\bar{u}_R\mathcal{O}_L + \text{h.c.}$$

$$\mathcal{O} \sim \psi\chi\chi\,,\ \chi\psi\chi$$

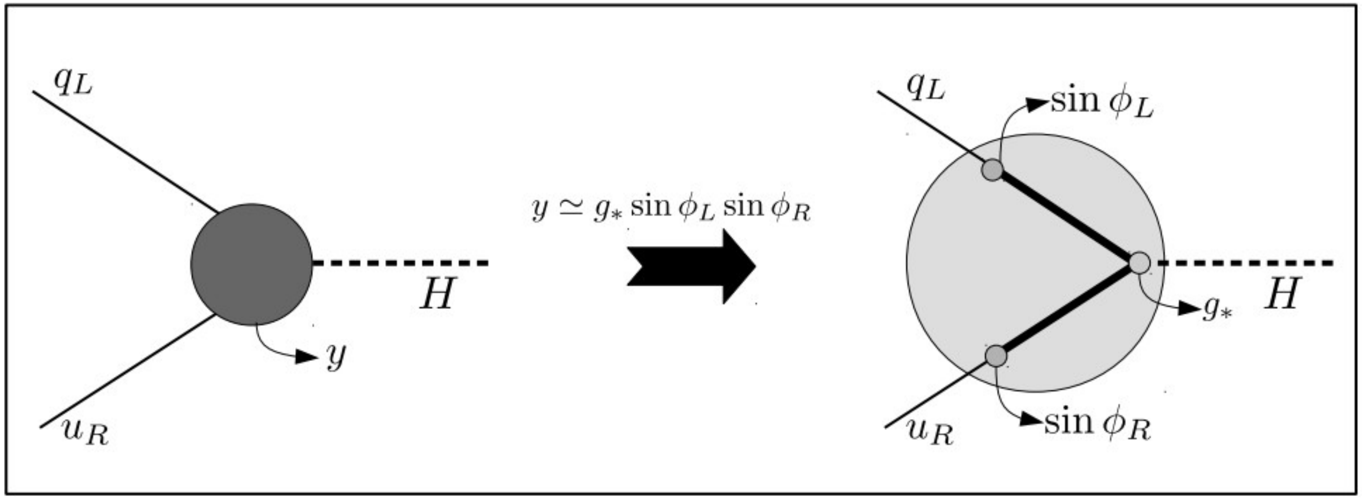
Trilinear fermionic operators give rise to vector-like fermionic bound states (top-partners) below the confinement scale

χ carries the SU(3) color quantum numbers, ψ does not.

Since we want to obtain the top partners, we also need to embed the color group SU(3)c into the global symmetry

$3\ (\chi_\alpha, \tilde{\chi}_\alpha)$ Complex	$SU(3)\times SU(3)' \to SU(3)_D \equiv SU(3)_c$
$6\ \chi_\alpha$ Pseudoreal	$SU(6) \to Sp(6) \supset SU(3)_c$
$6\ \chi_\alpha$ Real	$SU(6) \to SO(6) \supset SU(3)_c$

Yukawa couplings



- SM fermions : massive after EWSB

$$m_q \sim v\lambda_L\lambda_R \left(\frac{m_*}{\Lambda_{\mathrm{UV}}}\right)^{d_L+d_R-5}$$

- Interaction with Higgs via composite resonances
- Top can be substantially composite, while other light quarks are mostly elementary

Low energy theory of VLQs

Building blocks for IR theory

Three basic ingredients to construct the IR Lagrangian of VLQs and pNGBs

- **pNGB matrix (fixed by the choice of coset G/H)**

$$\Sigma = \Omega(\xi) \exp\left(\frac{i\pi_a \hat{T}^a}{f}\right), \qquad \Sigma \to g\Sigma h^{-1}(\pi)$$

- **Irrep of the vector-like partners under unbroken H**

$$\Psi_N \to \Psi_N, \quad \Psi_F \to h\Psi_F, \quad \Psi_{A/S} \to h\Psi_{A/S}h^T, \quad \Psi_D \to h\Psi_D h^\dagger$$

- **Spurion embedding of SM quarks in the global symmetry G**

$$q_L \to t_L S_{t_L} + b_L S_{b_L}, \qquad t_R \to t_R S_{t_R} \qquad b_R \to b_R S_{b_R}$$

$$N \to N, \quad F \to gF, \quad A \to gAg^T, \quad S \to gSg^T, \quad D \to gDg^\dagger$$

Lagrangian @TeV scale

$$\mathcal{L}_{\Psi^2} = \mathrm{tr}\left[\bar{\Psi} i D \Psi\right] - M \mathrm{tr}\left[\bar{\Psi}\Psi\right] + \kappa \mathrm{tr}\left[\bar{\Psi}\partial\Sigma\Psi\right]$$

$$\mathcal{L}_{\mathrm{elem.}} = \bar{q}_L i \not{D} q_L + \bar{t}_R i \not{D} t_R + \bar{b}_R i \not{D} b_R$$

$$\mathcal{L}_{\mathrm{P.C.}} = y_L f \bar{q}_L \Sigma \Psi_R + y_R f \bar{\Psi}_L \Sigma t_R$$

$$\mathcal{L} = \mathcal{L}_{\mathrm{pNGB}} + \mathcal{L}_{\mathrm{anom.}} + \mathcal{L}_{\mathrm{elem.}} + \mathcal{L}_{\Psi^2} + \mathcal{L}_{\mathrm{P.C.}} - V_{\mathrm{pot.}}$$

$$\mathcal{L}_{\mathrm{pNGB}} = \frac{f^2}{2} \mathrm{tr}\left[(D_\mu\Sigma)^\dagger (D^\mu\Sigma)\right]$$

$$V_{\mathrm{pot.}} = \frac{1}{2} m_h^2 h^2 + \frac{1}{2} m_i^2 \pi_i^2 + \mathcal{O}(\pi^3, \pi^4)$$

$$\mathcal{L}_{WZW} = \pi_i^0 \left[c_{\gamma\gamma} F\tilde{F} + c_{ZZ} Z\tilde{Z} + c_{Z\gamma} F\tilde{Z} + c_{WW} W^+ \tilde{W}^-\right] + \pi_i^+ \left[c_{ZW} Z\tilde{W}^- + c_{\gamma W} F\tilde{W}^-\right] + \pi_i^{++}\left[c_{W^-W^-} W^- \tilde{W}^-\right]$$

[AB, D B Franzosi, G Ferretti 2202.00037]

Specific example: SU(5)/SO(5)

- **pNGBs:** only the doublet Higgs receives vev

$$\mathbf{14} \xrightarrow{\mathrm{SU(2)_L\times SU(2)_R}} (\mathbf{3},\mathbf{3})+(\mathbf{2},\mathbf{2})+(\mathbf{1},\mathbf{1}) \xrightarrow{\mathrm{SU(2)_L\times U(1)_Y}} \mathbf{3}_0(\Phi_0)+\mathbf{3}_{\pm1}(\Phi_\pm)+\mathbf{2}_{\pm1/2}(H)+\mathbf{1}_0(\eta)$$

$$\xrightarrow{\mathrm{SU(2)_C}} \mathbf{1}(\chi_1^0)+\mathbf{3}(\chi_3^\pm,\chi_3^0)+\mathbf{5}(\chi_5^{\pm\pm},\chi_5^\pm,\chi_5^0)+\mathbf{1}(h)+\mathbf{3}(G^\pm,G^0)+\mathbf{1}(\eta)$$

- **Top-partners:** transform under unbroken SO(5)

$\mathrm{SO(5)\times U(1)_X}$	$\mathrm{SU(2)_L\times SU(2)_R\times U(1)_X}$	$\mathrm{SU(2)_L\times U(1)_Y}$
$\mathbf{1}_{\frac{2}{3}}$	$\to(\mathbf{1},\mathbf{1})_{\frac{2}{3}}$	$\to\mathbf{1}_{\frac{2}{3}}$
$\mathbf{5}_{\frac{2}{3}}$	$\to(\mathbf{1},\mathbf{1})_{\frac{2}{3}}+(\mathbf{2},\mathbf{2})_{\frac{2}{3}}$	$\to\mathbf{1}_{\frac{2}{3}}+\mathbf{2}_{\frac{1}{6}}+\mathbf{2}_{\frac{7}{6}}$
$\mathbf{10}_{\frac{2}{3}}$	$\to(\mathbf{2},\mathbf{2})_{\frac{2}{3}}+(\mathbf{3},\mathbf{1})_{\frac{2}{3}}+(\mathbf{1},\mathbf{3})_{\frac{2}{3}}$	$\to\mathbf{1}_{\frac{2}{3}}+\mathbf{1}_{\frac{5}{3}}+\mathbf{1}_{-\frac{1}{3}}+\mathbf{2}_{\frac{1}{6}}+\mathbf{2}_{\frac{7}{6}}+\mathbf{3}_{\frac{2}{3}}$
$\mathbf{14}_{\frac{2}{3}}$	$\to(\mathbf{1},\mathbf{1})_{\frac{2}{3}}+(\mathbf{2},\mathbf{2})_{\frac{2}{3}}+(\mathbf{3},\mathbf{3})_{\frac{2}{3}}$	$\to\mathbf{1}_{\frac{2}{3}}+\mathbf{2}_{\frac{1}{6}}+\mathbf{2}_{\frac{7}{6}}+\mathbf{3}_{\frac{2}{3}}+\mathbf{3}_{\frac{5}{3}}+\mathbf{3}_{-\frac{1}{3}}$

- **Spurions:** no vev for the triplet, no corrections to Zbb

$$\hat{q}_L = t_L D^1_{t_L} + b_L D^1_{b_L} \in \mathbf{24}, \quad \hat{t}_R = t_R D^2_{t_R} \in \mathbf{24}$$

Fermion mass-matrix

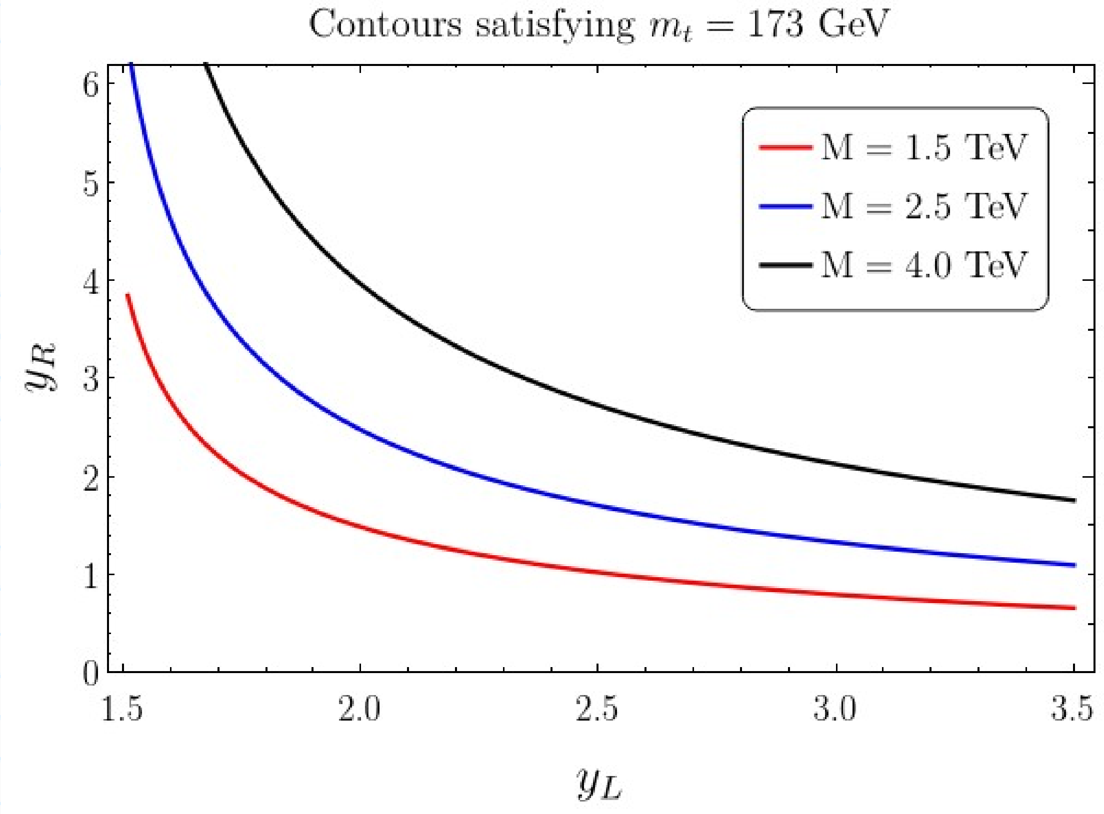
$$\mathcal{M}_{2/3} = \left(\begin{array}{c|c} 0 & \omega_L^t(v)^T \\ \hline \omega_R^t(v) & M\mathbb{I}_{n-1} \end{array}\right)$$

- (n-3) degenerate states with mass M
- One state shifted by ~ y^2v^2
- Others shifted by ~ y^2f^2

$$\mathcal{M}_{-1/3} = \left(\begin{array}{c|c} y_b v & \omega_L^b(v)^T \\ \hline 0_{n-1\times 1} & M\mathbb{I}_{n-1} \end{array}\right)$$

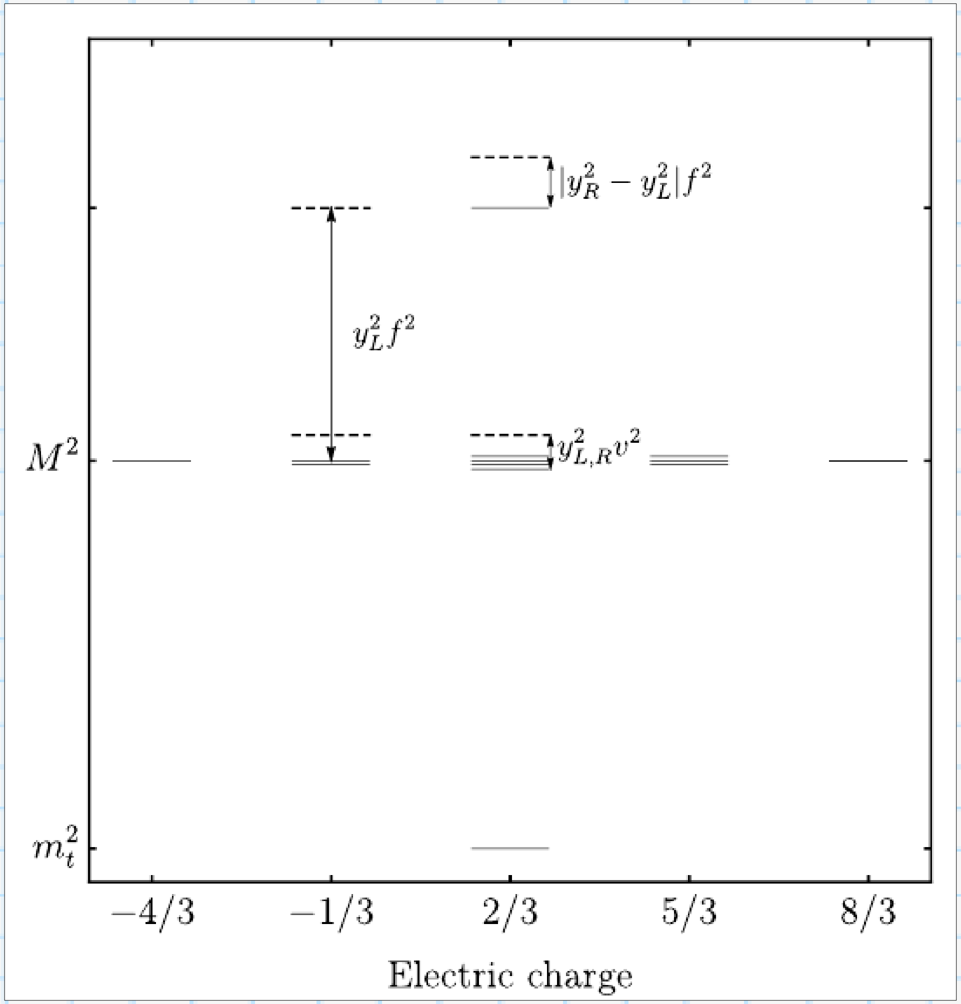
- (n-2) degenerate states with mass M

$$m_t \propto \frac{f y_L y_R v}{\sqrt{M^2 + y^2 f^2}}$$



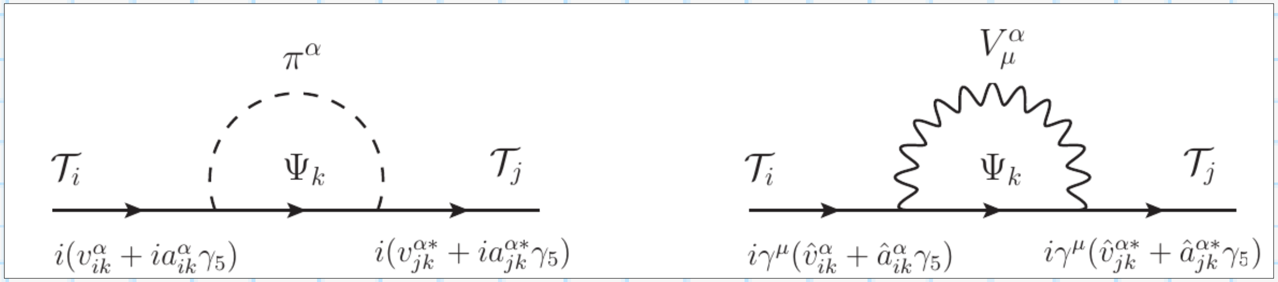
Light top-partners are usually required to reproduce correct top mass

VLQ spectrum



Features of the VLQ spectrum:

- **Universality** (little dependence on Coset choice or representation)
- Existence of **degenerate states** at Tree level
- **One loop corrections** to mass break the degeneracy
- Mixing between nearly degenerate states leads to **off-diagonal self-energy**



$$\left[\frac{i(\not{p} + M_{\mathcal{T}})}{(p^2 - M_{\mathcal{T}}^2)\mathbb{1} + i M_{\mathcal{T}} (\Gamma_{\mathcal{T}} + 2i\delta M)} \right]_{ij}$$

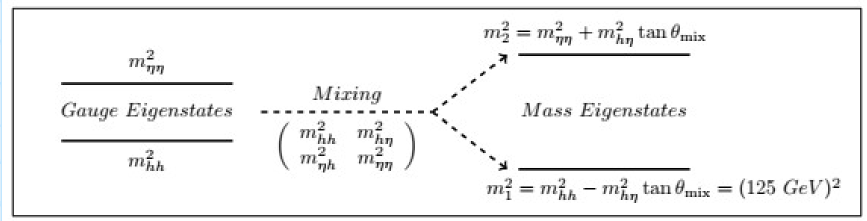
Higgs: too light to be composite ?

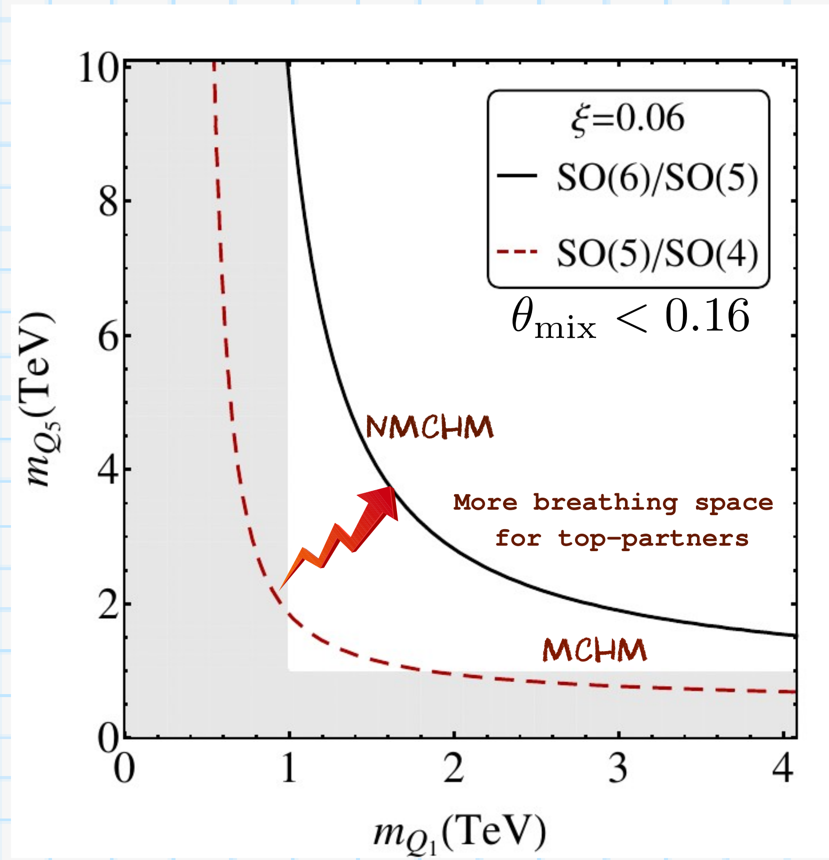
- **Higgs mass scales as:**

$$m_h^2 \sim \frac{N_c}{\pi^2}\frac{m_t^2 m_Q^2}{f^2}$$

Light top-partners **Large Fine-tuning**

Light Higgs

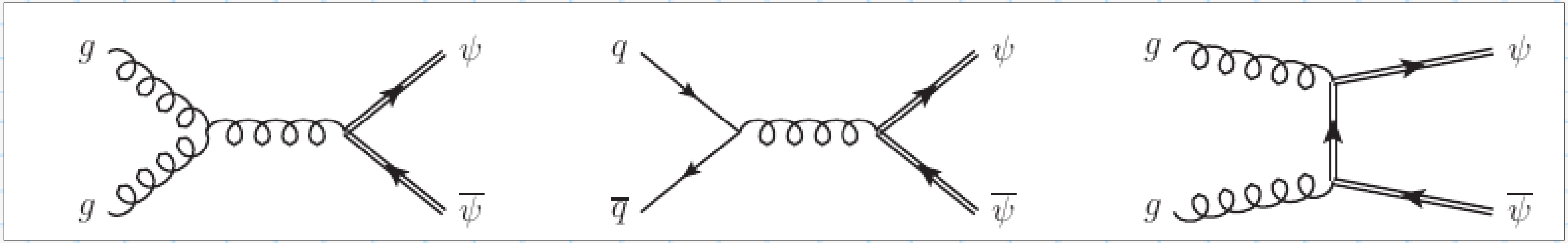


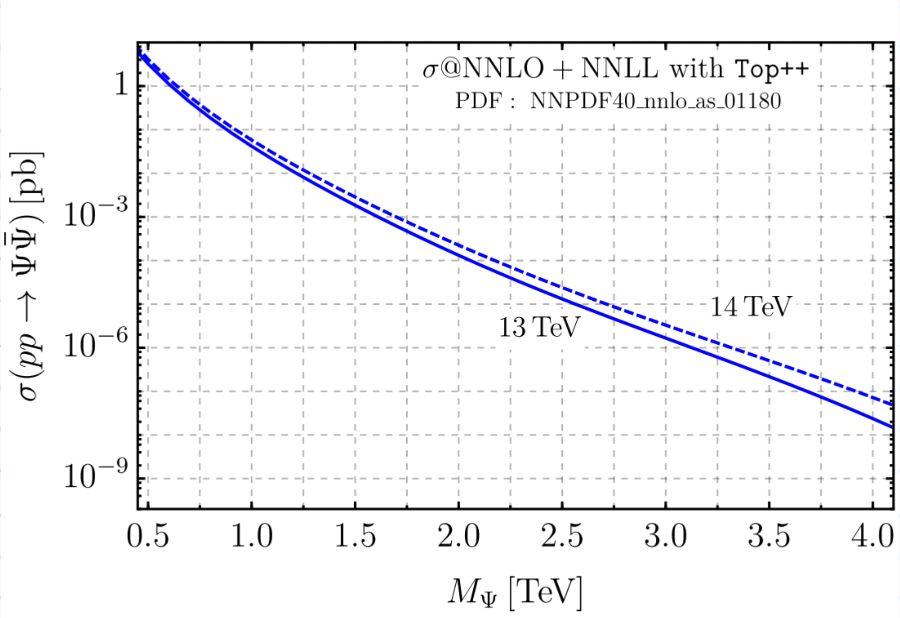


[AB, G Bhattacharyya, T S Ray 1703.08011]

Production and decays of VLQs

- **Pair production of VLQs at LHC: depends only on VLQ mass**





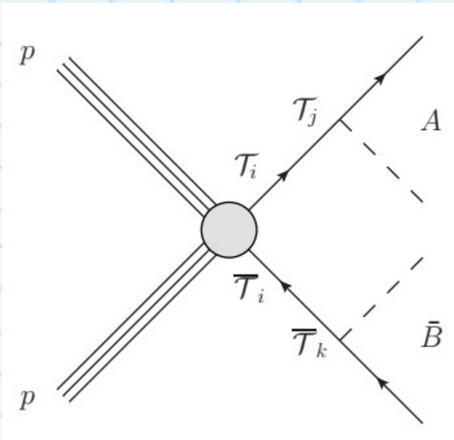
- **Possible decay channels**

Top-partner	Decays to SM final states	Decays to BSM final states
$T_{\frac{2}{3}}, X_{\frac{2}{3}}, Y_{\frac{2}{3}}, \tilde{T}_{\frac{2}{3}}$	$th,\ tZ,\ bW^+$	$t\chi^0_{1,3,5},\ t\eta,\ b\chi^+_{3,5}$
$B_{-\frac{1}{3}}, Y_{-\frac{1}{3}}, \tilde{B}_{-\frac{1}{3}}$	$tW^-,\ bh,\ bZ$	$t\chi^-_{3,5},\ b\chi^0_{1,3,5}\ ,\ b\eta$
$X_{\frac{5}{3}}, Y_{\frac{5}{3}}, \tilde{X}_{\frac{5}{3}}$	tW^+	$t\chi^+_{3,5},\ b\chi^{++}_5$

f	M	m_3	m_5	m_1	m_η	y_L	y_R	κ
1000	1500	330	315	335	290	1.80	1.87	0.50

- **Single production: Typically model dependent**

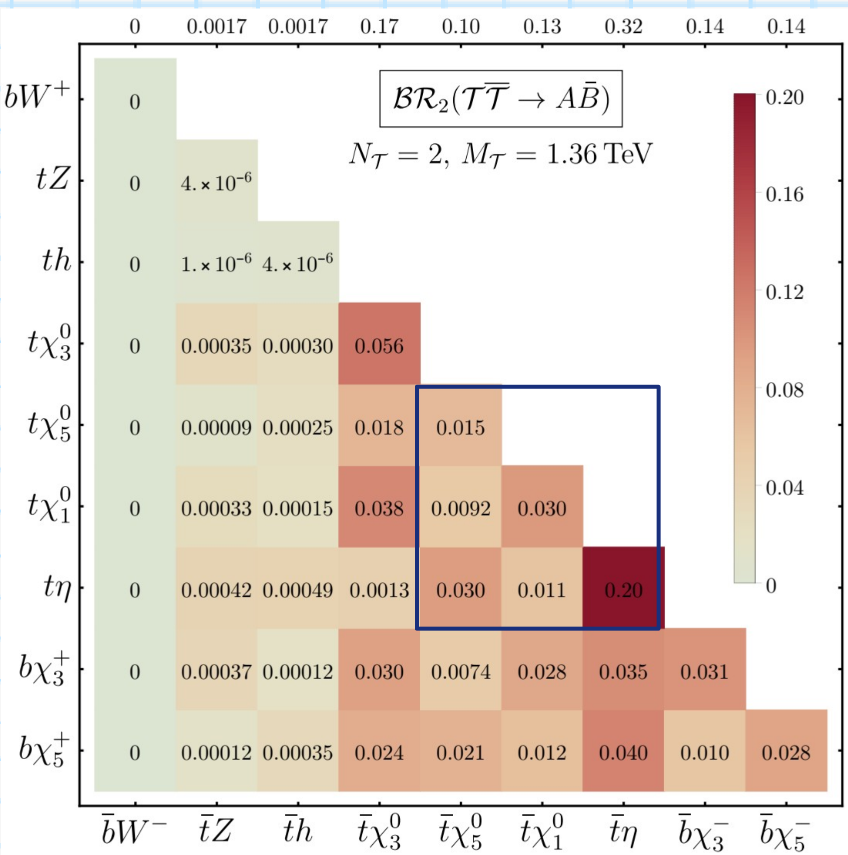
Decays of nearly degenerate states



- **Theoretical Challenges:**

$$\left[\frac{i(\not{p}+M_{\mathcal{T}})}{(p^2-M_{\mathcal{T}}^2)\mathbb{1}+iM_{\mathcal{T}}(\Gamma_{\mathcal{T}}+2i\delta M)}\right]_{ij}$$

- ✓ **Deal with the nearly degenerate states**
- ✓ **One-loop self energy is off-diagonal**
- ✓ **Consider matrix Breit-Wigner propagators**



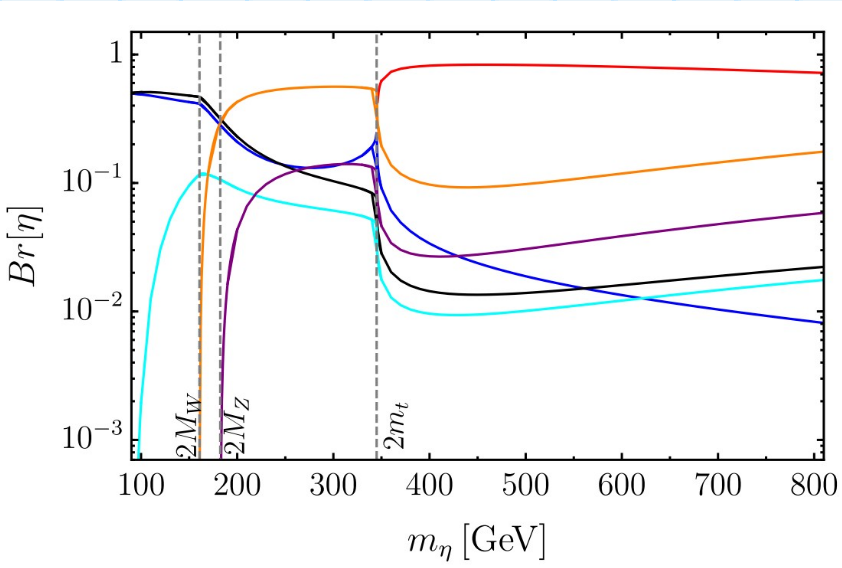
$$\sigma(pp \to \mathcal{T}\overline{\mathcal{T}} \to A\bar{B}) \overset{\text{NWA}}{=} N_{\mathcal{T}}\sigma(pp \to \mathcal{T}\overline{\mathcal{T}})\mathcal{BR}_2(\mathcal{T}\overline{\mathcal{T}} \to A\bar{B})$$

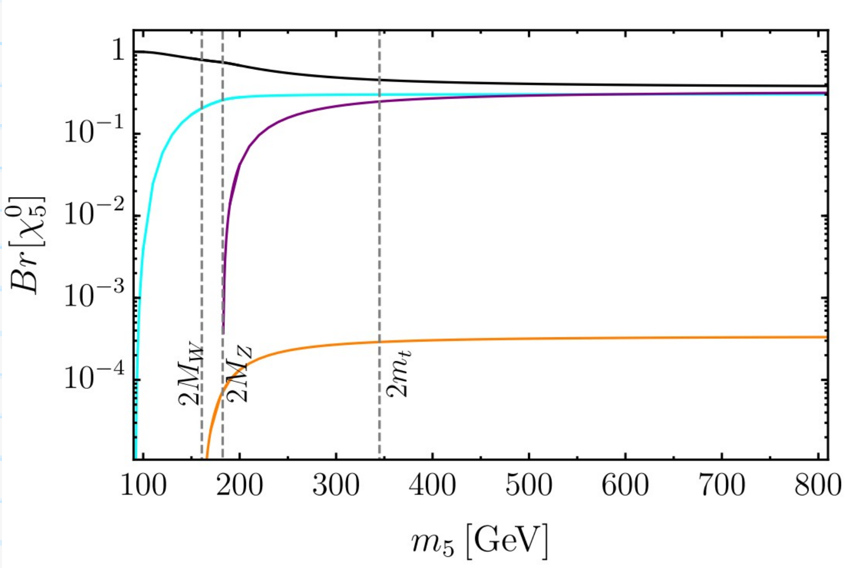
$$\mathcal{BR}(\mathcal{T} \to A) = \sum_{\bar{B}} \mathcal{BR}_2(\mathcal{T}\overline{\mathcal{T}} \to A\bar{B}) \qquad \sum_{A} \mathcal{BR}(\mathcal{T} \to A) = 1$$

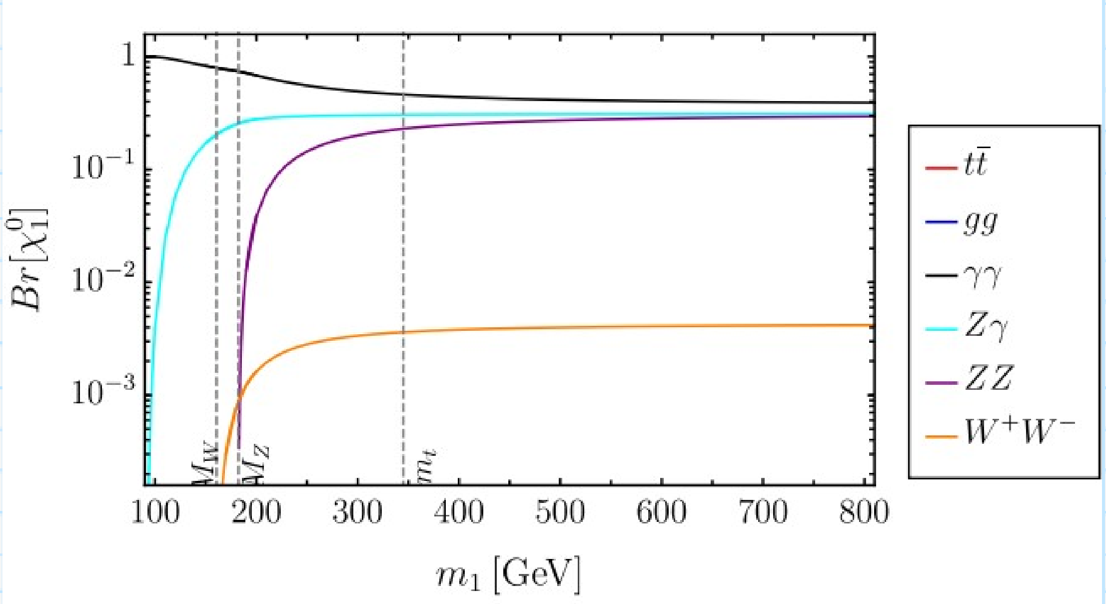
$$\mathcal{BR}_2(\mathcal{T}\overline{\mathcal{T}} \to A\bar{B}) \neq \mathcal{BR}(\mathcal{T} \to A)\mathcal{BR}(\bar{\mathcal{T}} \to \bar{B})$$

[AB, D B Franzosi, G Ferretti 2202.00037]

Branching ratios of pNGBs







- **Decays into diboson are mainly driven by anomaly terms**
- χ_5^0 **and** χ_1^0 **are fermiophobic**
- η **decays to gg through top loop**

Diphoton signal

$$\sigma\left(pp \to (t\gamma\gamma) + X\right) = \sum_{\pi^\alpha=\eta,\chi^0_{1,3,5}} \sum_{\bar{B}=\text{all}} \sigma\left(pp \to (t\pi^\alpha)\bar{B}\right) BR(\pi^\alpha \to \gamma\gamma),$$

$$= N_{\mathcal{T}}\sigma(pp \to \mathcal{T}\overline{\mathcal{T}}) \sum_{\pi^\alpha=\eta,\chi^0_{1,3,5}} \mathcal{BR}\left(\mathcal{T} \to t\pi^\alpha\right) BR(\pi^\alpha \to \gamma\gamma),$$

Relevant for leptonically decaying top, so that top and anti-top can be distinguished

$$\Longrightarrow \ \sigma\left(pp \to (t\gamma\gamma) + X\right) = 1.3 \text{ fb}$$

More inclusive quantity (relevant for hadronically decaying top):

$$\Longrightarrow \ \sigma\left(pp \to (t/\bar{t}\gamma\gamma) + X\right) = 2.4 \text{ fb}$$

These numbers are in the ballpark region of interest for VLQ searches by ATLAS and CMS collaborations

Summary

- Composite pNGB Higgs from confining gauge theory: non-SUSY alternative to address hierarchy problem, partial compositeness mechanism can give mass to quarks and trigger EWSB through one loop potential.
  Major experimental signature arises from BSM pNGBs, colored VLQs and modifications in Higgs couplings.

- We construct generic low energy Lagrangian to bridge the gap between simplified models and specific models of partial compositeness.

- Mass matrix and spectrum of the VLQs are generic, typically exhibits a number of nearly degenerate VLQs. This leads to theoretical challege to compute cross sections incorporating full quantum interference effects.

- Motivated models lead to interesting non-standard search topologies involving VLQs decaying into BSM pNGBs, followed by pNGBs decaying to diboson.

- Amongst the most promising signatures at the LHC are final states containing a diphoton resonance along with a top quark.

Thank you!