CHASING THE HIGGS SHAPE @ LHC

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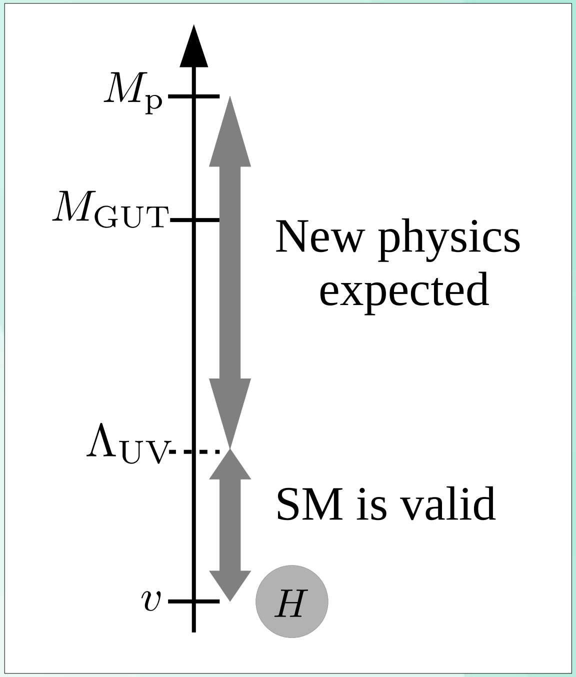
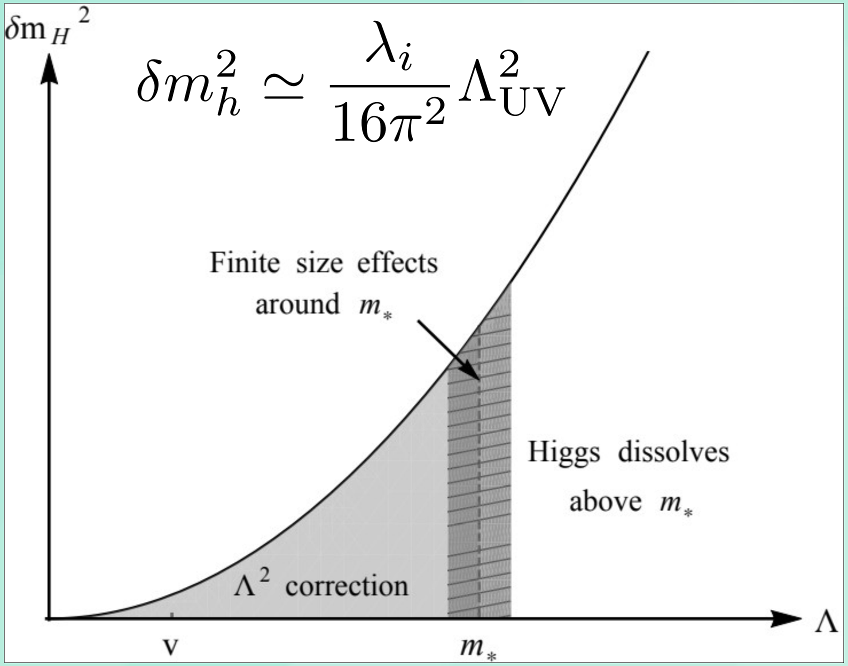
Outline of the talk

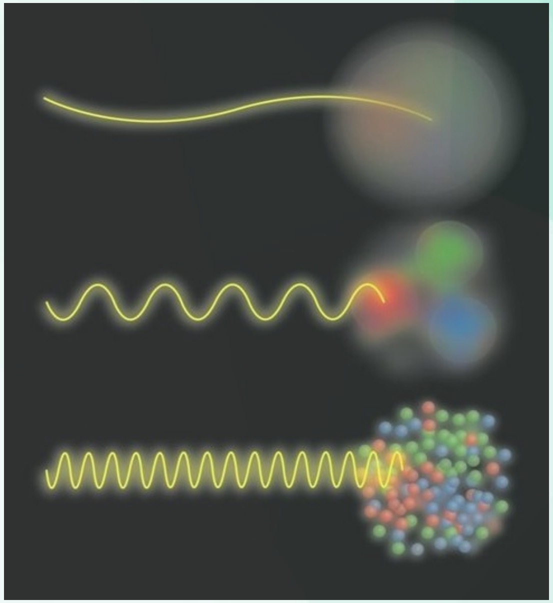
- **Composite Higgs models**
    - ➔ Motivation and construction
    - ➔ Phenomenological implications
- **Higgs coupling modifications**
    - ➔ Status after LHC Run 2
    - ➔ Form factors and differential distributions
- **IR theory of top-partners (VLQs)**
    - ➔ IR Lagrangian and VLQ spectrum
    - ➔ Possible signatures
- **Summary**

Composite Higgs Models

Composite Higgs motivations

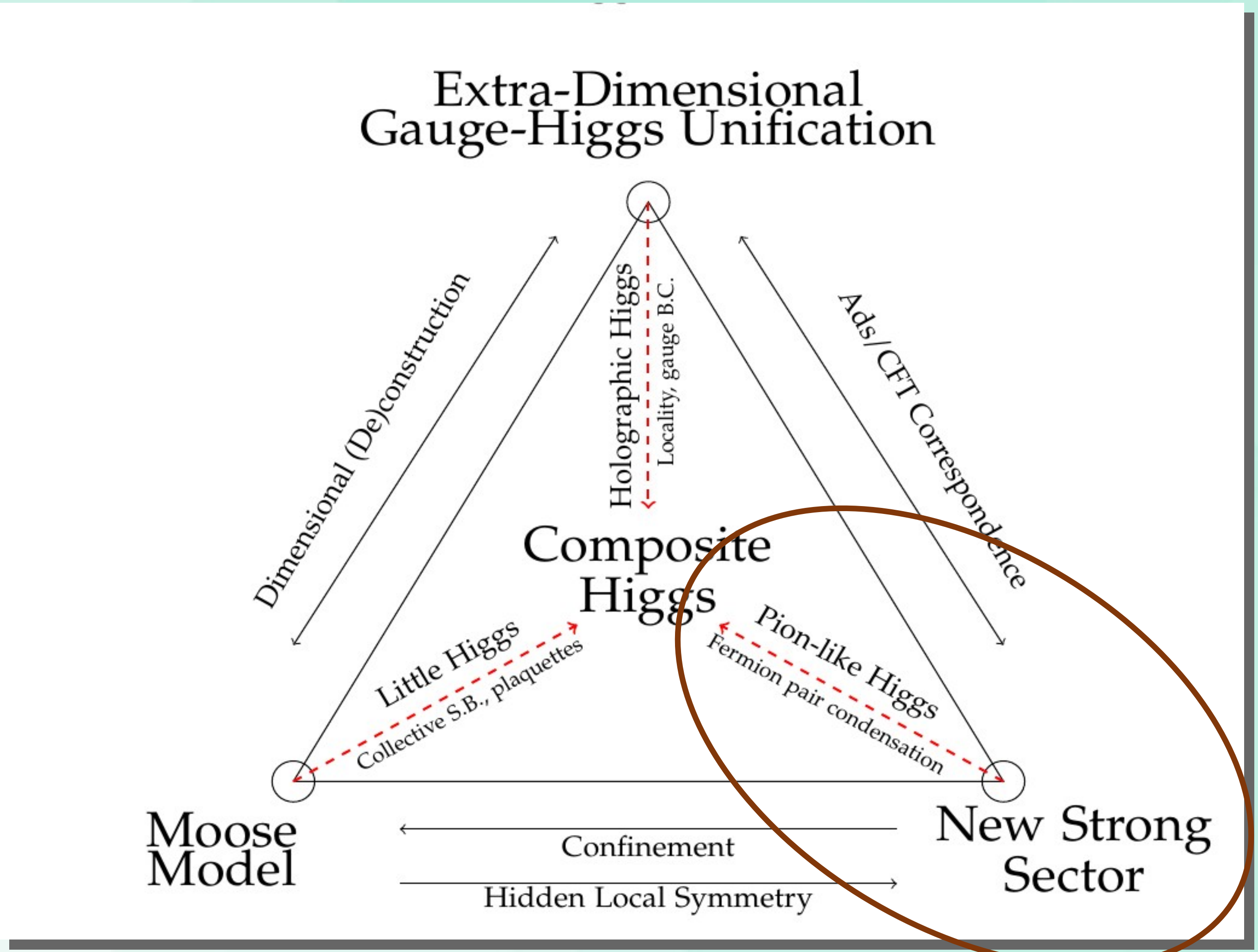






- **Higgs is a composite bound state of a strongly interacting sector**
- **Higgs emerges as a pseudo Nambu-Goldstone boson (pNGB)**

Multifaceted framework



Taken from Ph.D. Thesis of D T Murnane

Comparison with QCD

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 (VLQ)
Vacuum misalignment	No	Yes (triggers EWSB)

Partial compositeness

Examples of cosets

Three minimal cosets from 4D strongly coupled gauge theories
(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	$SU(5)/SO(5)$

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

- **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]

Top-partners (VLQs)

Partial compositeness

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

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

Trilinear fermionic operators

SU(3) colored

Embedding of 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	$SU(6) \to SO(6) \supset SU(3)_c$

See Werner's talk for more details

Phenomenological implications

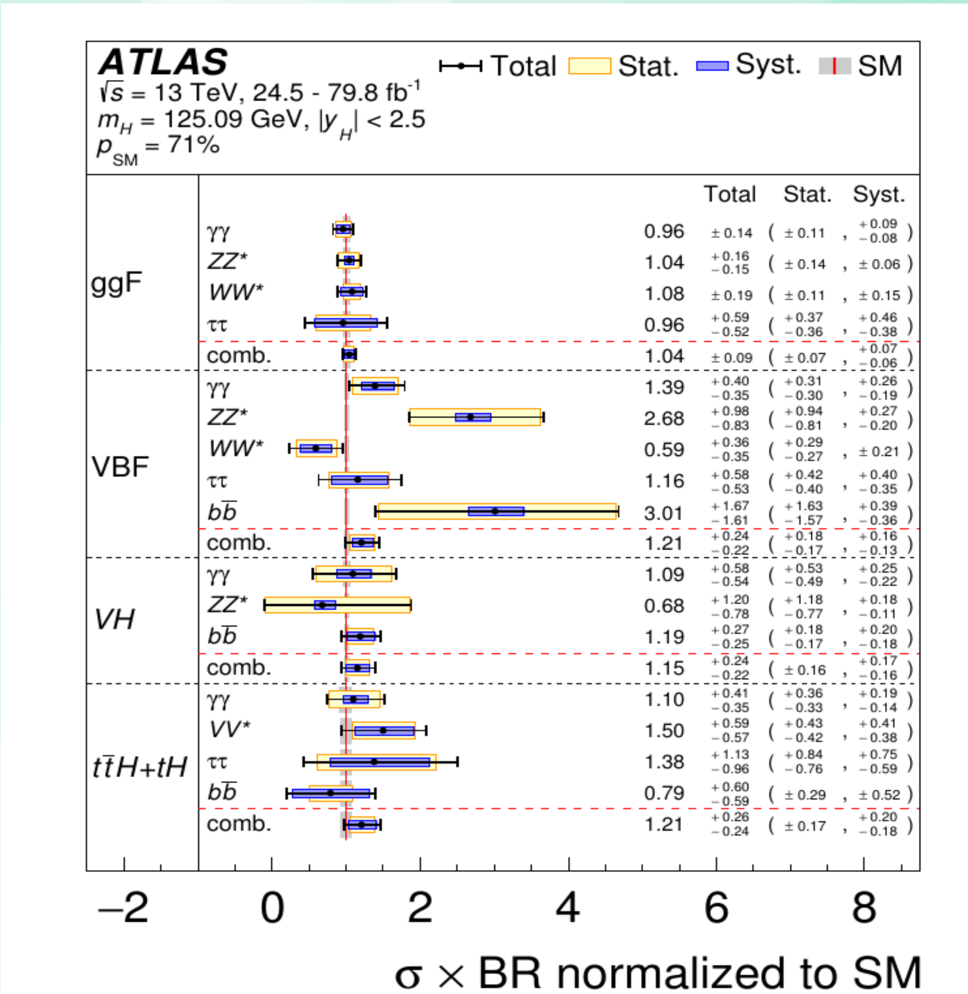
- Modification of Higgs couplings to other SM particles due to pNGB nature.
- All the coupling measurements at LHC show strong affinity towards the SM values.

- Presence of non-Standard scalars, vectors and 'colored' fermions (LHC search program).
- Absence of any signatures at LHC put lower bounds on the mass of the heavy states.

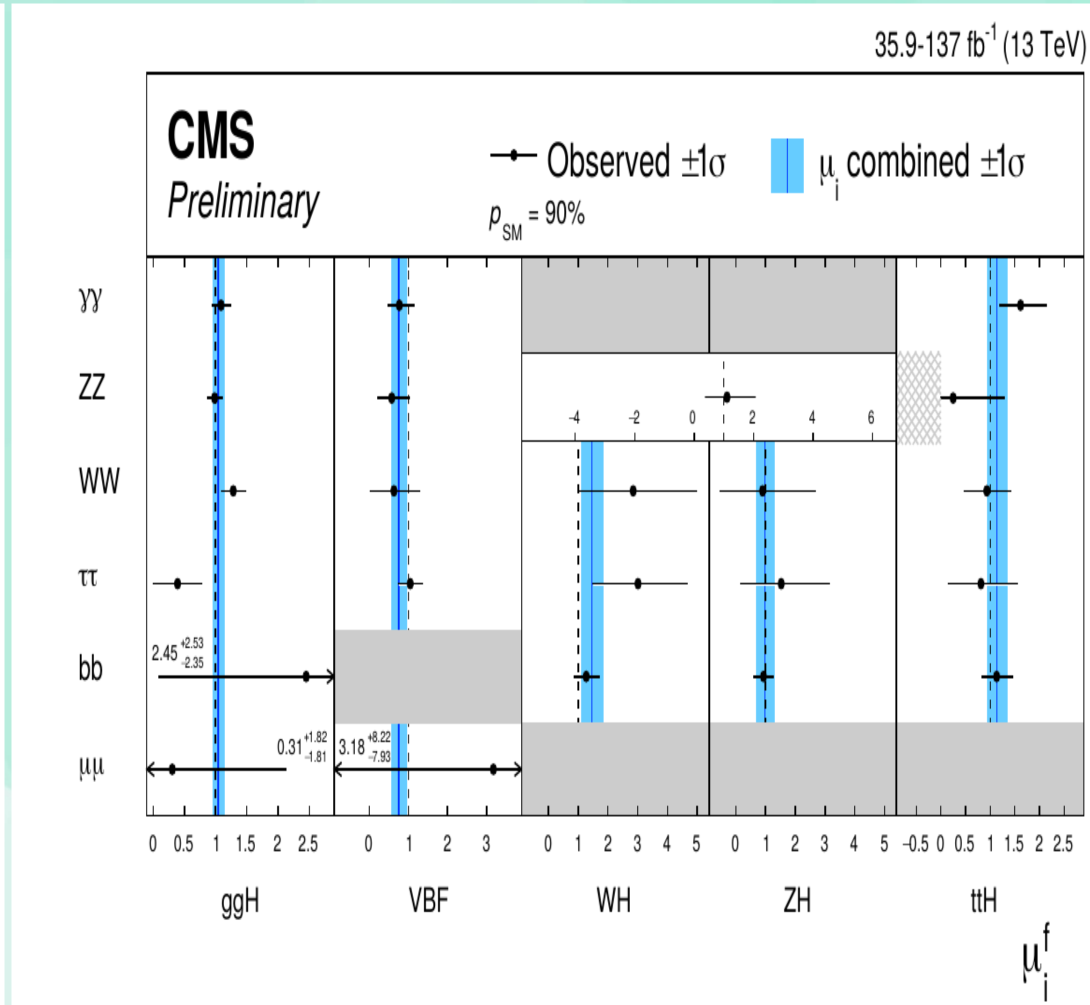
Higgs coupling modifications

Higgs data @Run 2

1909.02845



CMS−PAS−HIG−19−005



Modification of Higgs couplings

- **Mixing with other spin-0 bosons,**

  Examples: models with additional SU(2)×U(1) multiplets.

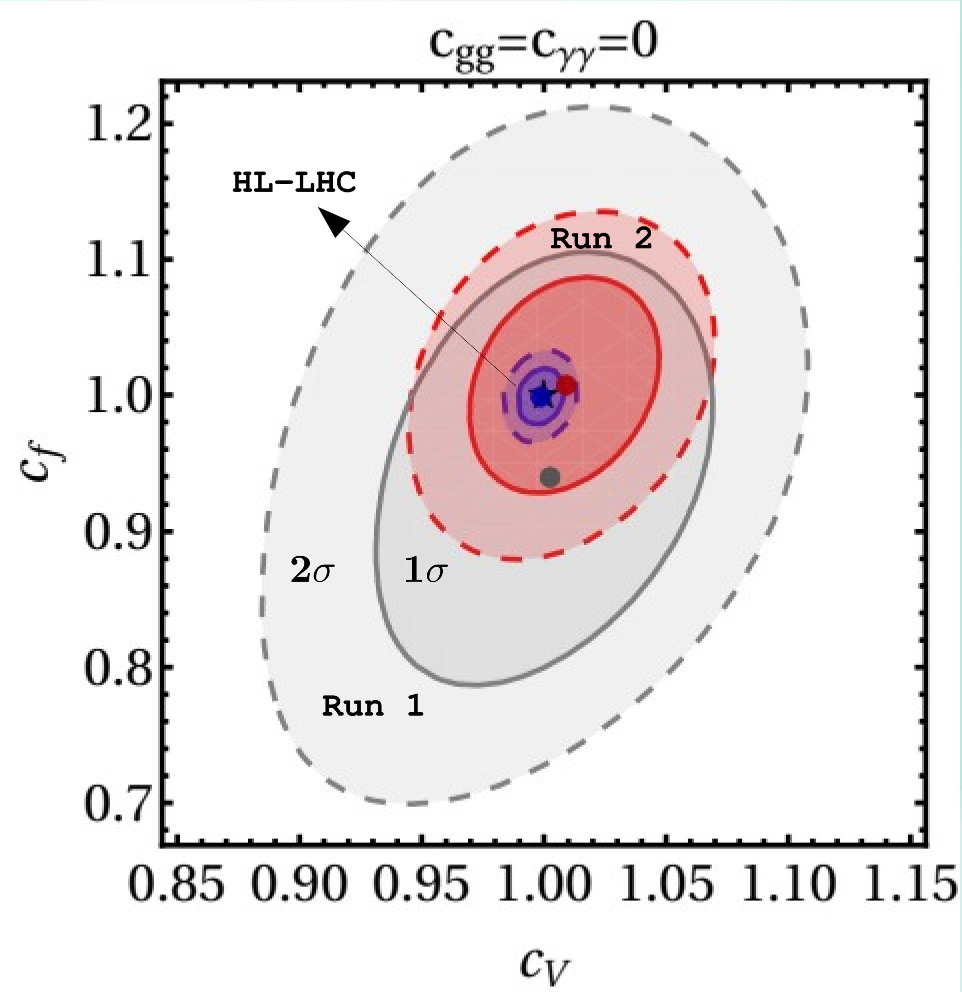
- **Higher dimensional operators, obtained by integrating out heavy degrees of freedom,**

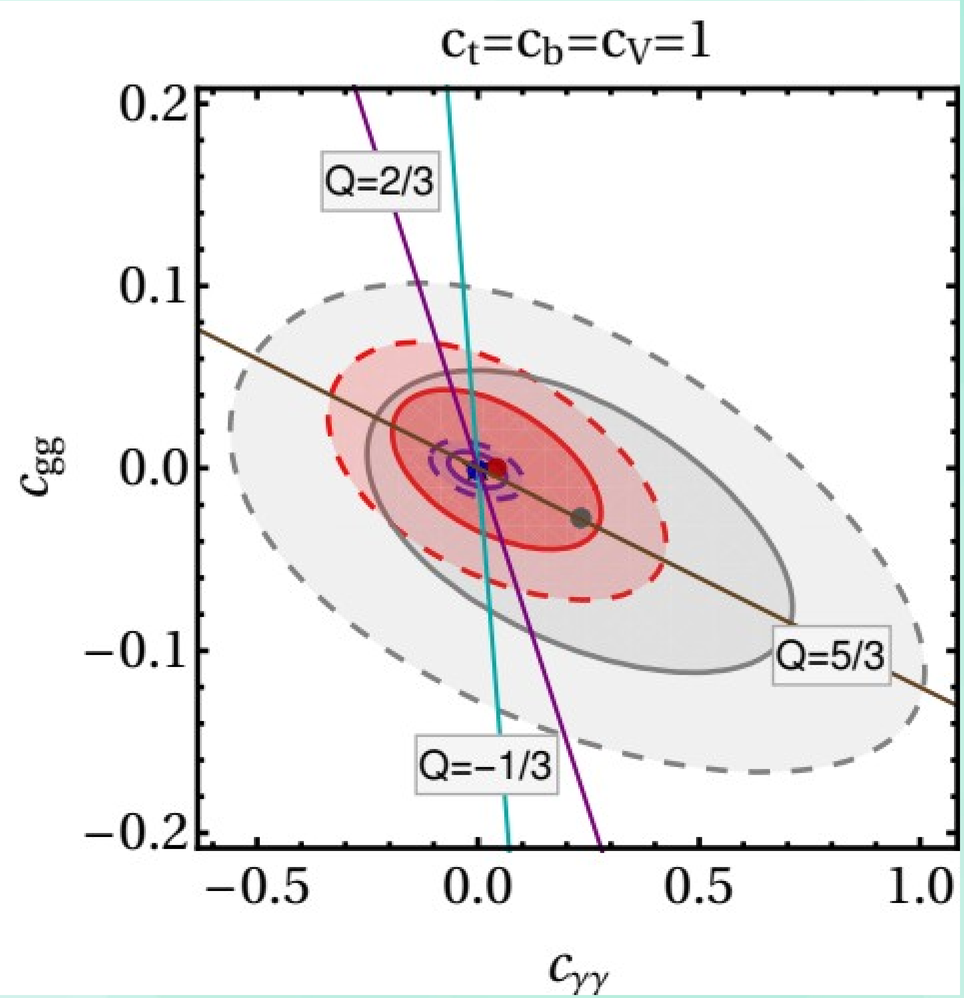
  Example: Composite Higgs scenario

$$\mathcal{L}_{(0)} = \frac{h}{v}\left[c_V\left(2M_W^2 W_\mu^\dagger W^\mu + M_Z^2 Z_\mu Z^\mu\right) - \sum_f c_f m_f \bar{f} f\right]$$

$$\mathcal{L}_{(2)} = -\frac{h}{4\pi v}\left[\alpha_e c_{\gamma\gamma} F_{\mu\nu}F^{\mu\nu} + \alpha_e c_{Z\gamma} Z_{\mu\nu}F^{\mu\nu} - \frac{\alpha_s}{2} c_{gg} G^a_{\mu\nu}G^{a\mu\nu}\right]$$

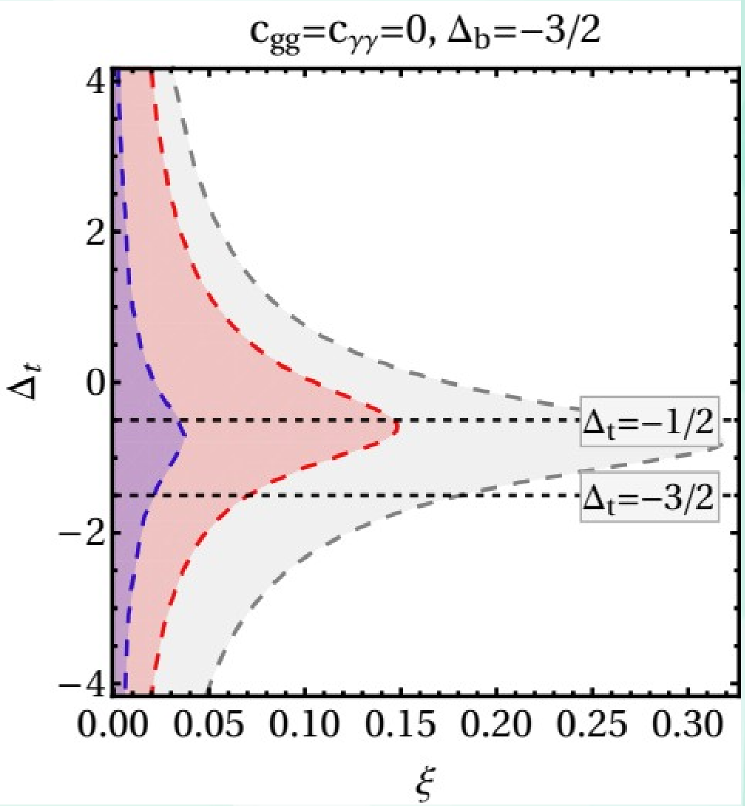
LHC Run 2 limits





AB, G Bhattacharyya [2006.01164]

Interpretation in composite Higgs

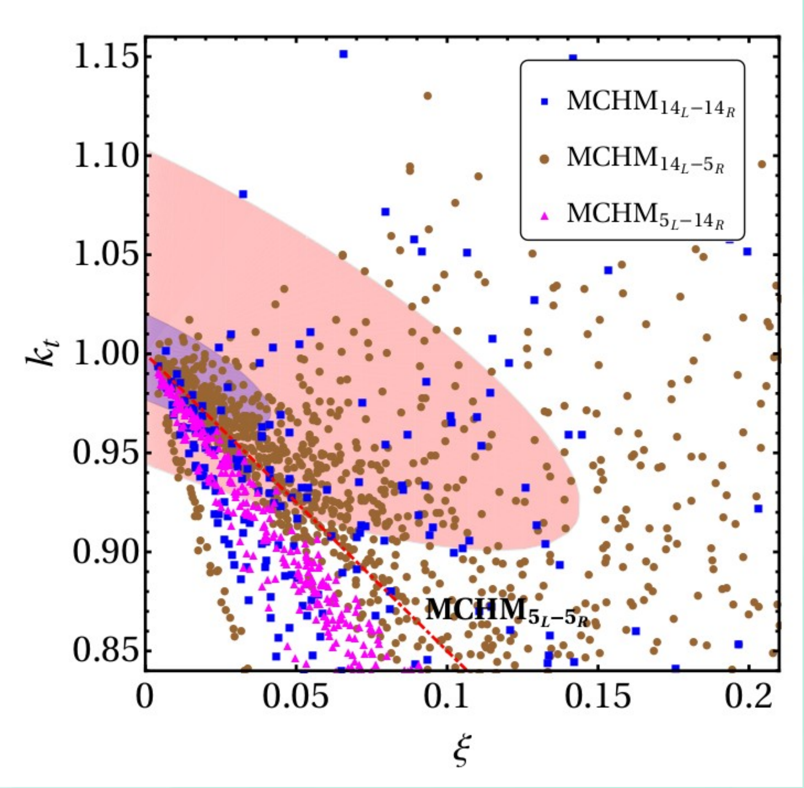


- **Higher dimensional operators from pNGB nature of Higgs**
- **Momentum dependence captured through form factors**

$$c_V = \sqrt{1-\xi}$$

$$c_f = 1 - \Delta_f \xi$$

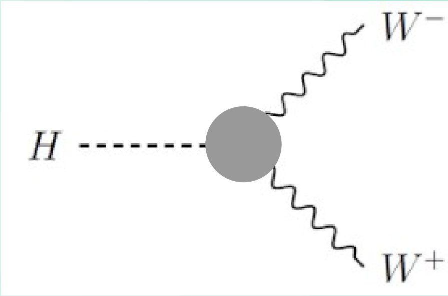
f > 1 TeV



Presence of more than one Yukawa invariant can somewhat relax the bound on f

AB, G Bhattacharyya, N Kumar, T S Ray [1712.07494]

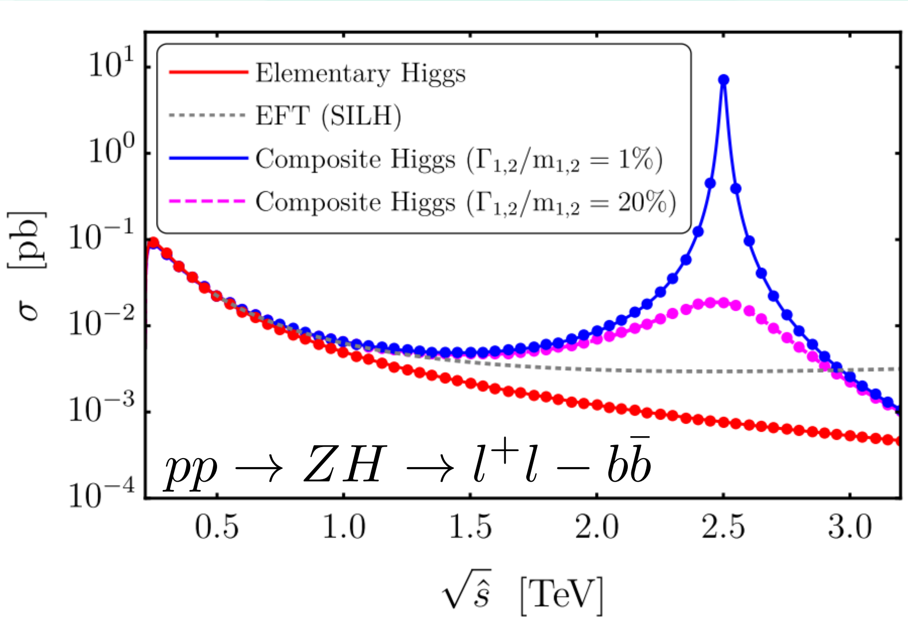
Momentum dependent form factors



$$g_V^{\rm SM}\frac{\Pi_V^{\mu\nu}(p_1,p_2)}{f^2}hV_\mu(p_1)V_\nu(p_2)$$

$$\Pi_V^{\mu\nu} \simeq \frac{f^2m^4}{(p_1^2-m^2+im\Gamma)(p_2^2-m^2+im\Gamma)}\left[\sqrt{1-\xi}\eta^{\mu\nu}+\frac{1}{m^2}\{c_2^V\,(\eta^{\mu\nu}p_1.p_2-p_2^\mu p_1^\nu)+c_3^V\,p_1^\mu p_2^\nu+c_4^V\,p_1^\mu p_1^\nu+c_5^V\,p_2^\mu p_2^\nu\}\right]$$

Form factors parametrize the information of strong dynamics

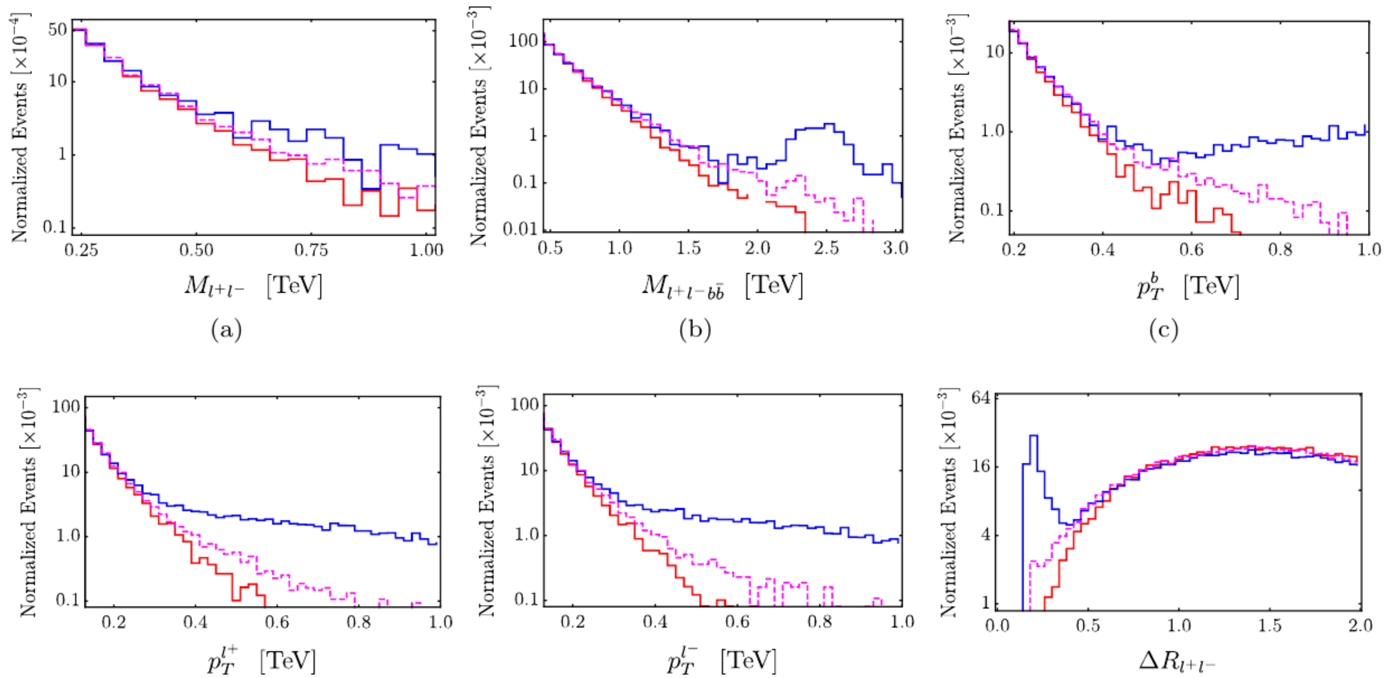


If the compositeness scale is just beyond the reach of LHC...
fineprints in differential distributions?

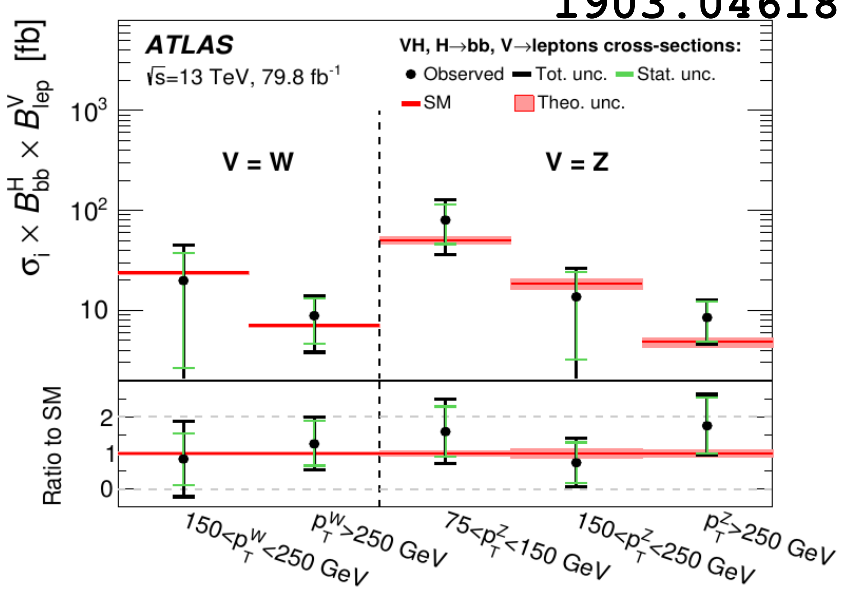
AB, S Dasgupta, T S Ray [2105.01093]

Differential distributions

AB, S Dasgupta, T S Ray [2105.01093]

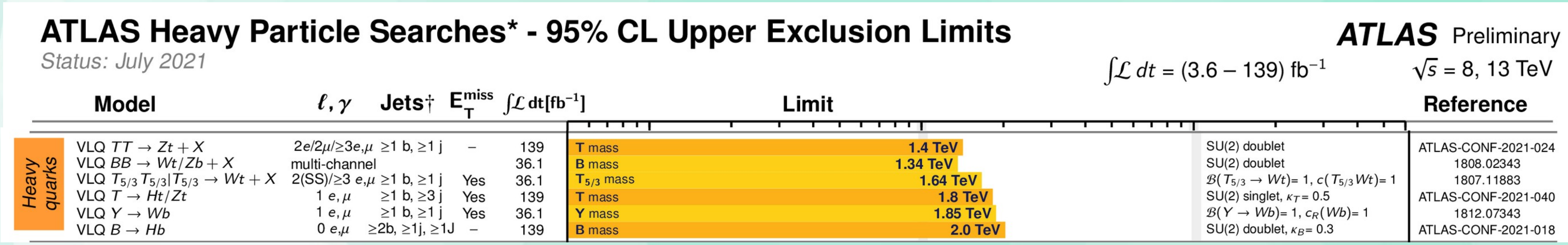


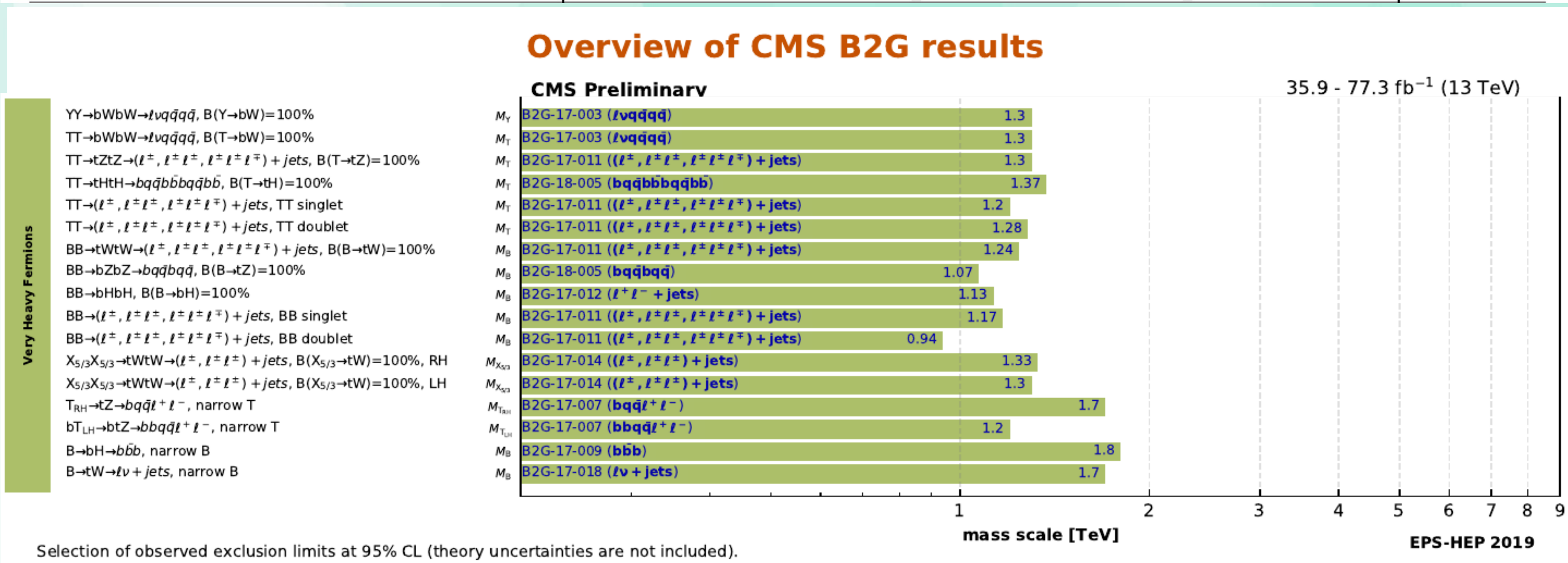
1903.04618



IR theory of top-partners (VLQs)

Status of VLQ search @LHC





Caveats:

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

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

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

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

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

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

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

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

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

[AB, D B Franzosi, G Ferretti 2202.00037]

Partial compositeness operators

Spurions	Ψ_N	Ψ_F	Ψ_A	Ψ_S
N	Ψ_N	$\times$	0	0
F	$\times$	$F^\dagger\Sigma\Psi_F$	$\times$	$\times$
A	$\text{tr}\left[A^\dagger\Sigma\epsilon\Sigma^T\right]\Psi_N$	$\times$	$\text{tr}\left[A^\dagger\Sigma\Psi_A\Sigma^T\right]$	0
S	$\text{tr}\left[S^\dagger\Sigma\epsilon\Sigma^T\right]\Psi_N$	$\times$	0	$\text{tr}\left[S^\dagger\Sigma\Psi_S\Sigma^T\right]$
D	0	$\times$	$\text{tr}\left[D^\dagger\Sigma\Psi_A\epsilon\Sigma^\dagger\right]$	$\text{tr}\left[D^\dagger\Sigma\Psi_S\epsilon\Sigma^\dagger\right]$

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

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

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

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

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

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

- **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 matrices

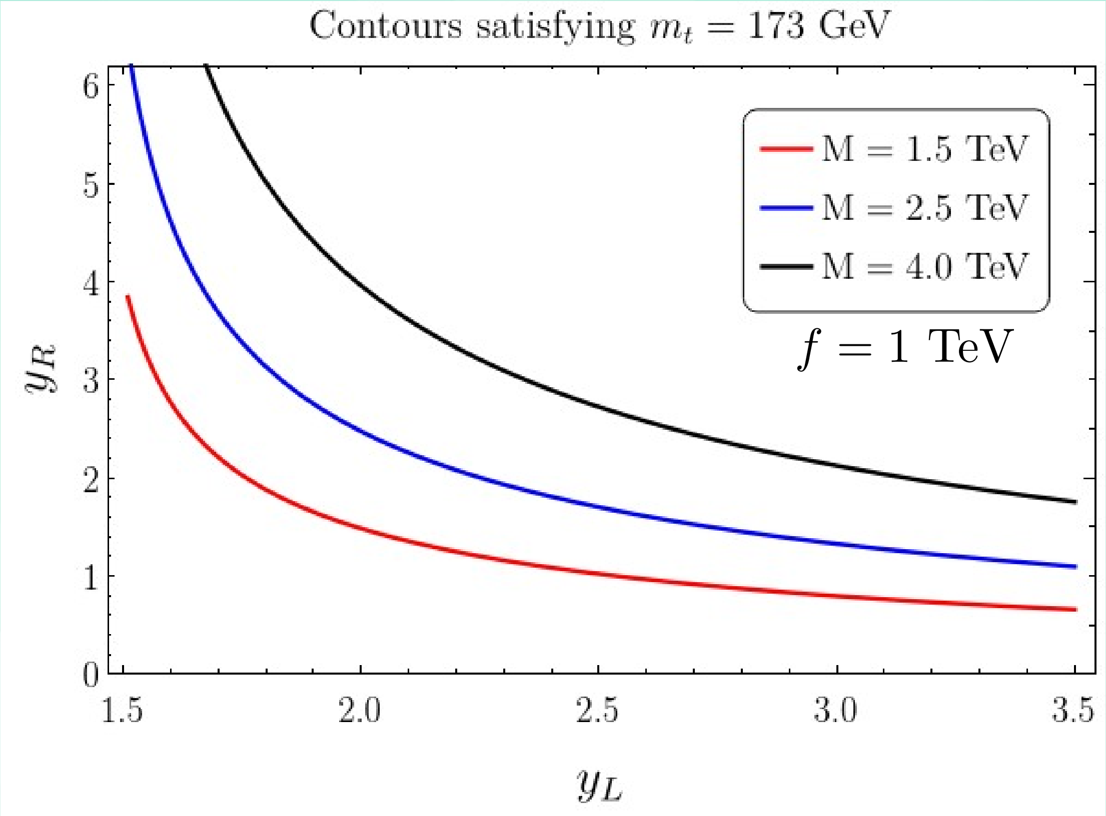
$$\mathcal{L}_{\text{P.C.}} = -M\bar{\Psi}\Psi + y_L f \bar{q}_L \Sigma \Psi_R + y_R f \bar{\Psi}_L \Sigma t_R \qquad m_t \propto \frac{f y_L y_R v}{\sqrt{M^2 + y^2 f^2}}$$

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

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

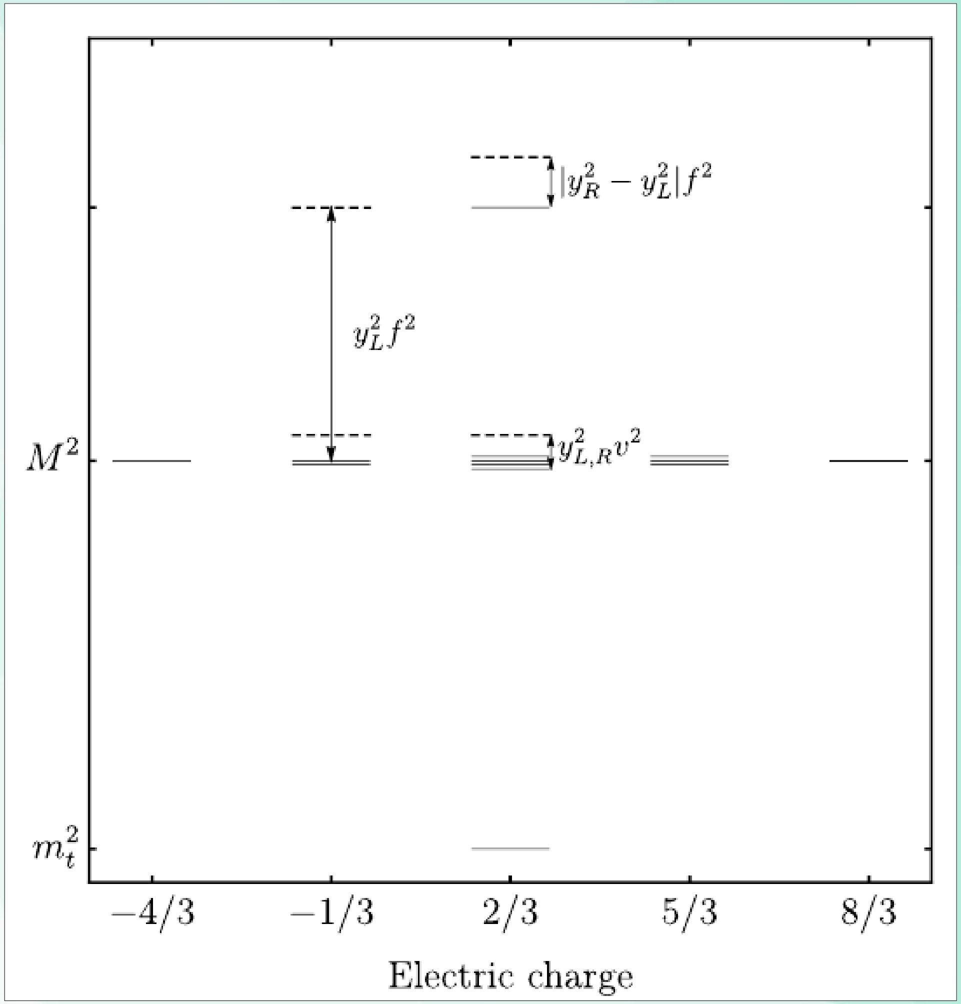
$$\mathcal{M}_{-1/3} = \left(\begin{array}{c|c} y_b v & y_L f_L^b(v)^T \\ \hline 0_{n-1\times 1} & M\mathbb{I}_{n-1} \end{array}\right)$$

- **(n-2) degenerate states with mass M**



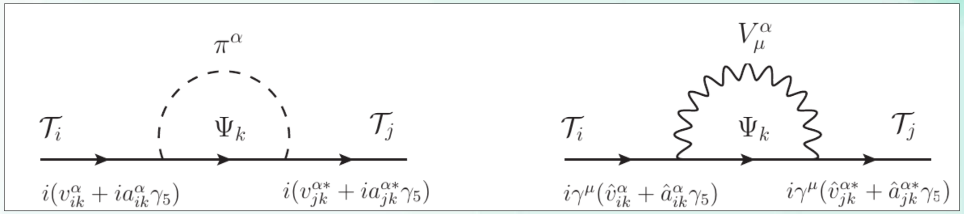
Light top-partners are usually required to reproduce correct top mass

VLQ spectrum



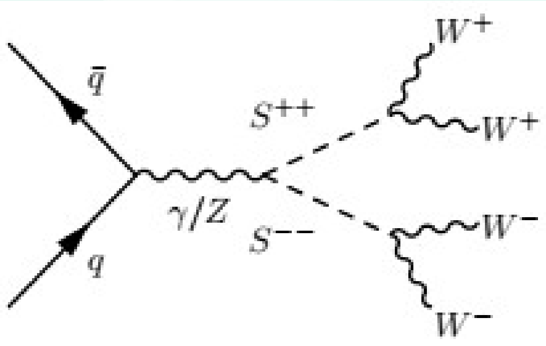
Features of the VLQ spectrum:

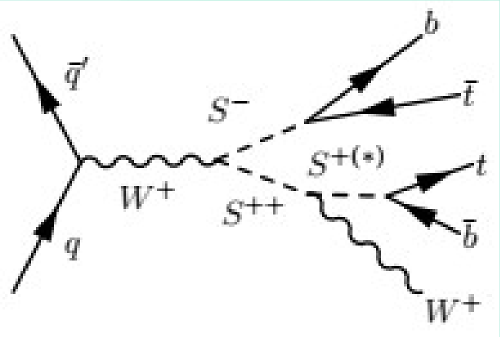
- Universality (little dependence on Coset choice or representation)
- Existence of degenerate states at Tree level
- One loop corrections to mass break the degeneracy
- Mixing between nearly degenerate states leads to off-diagonal self-energy

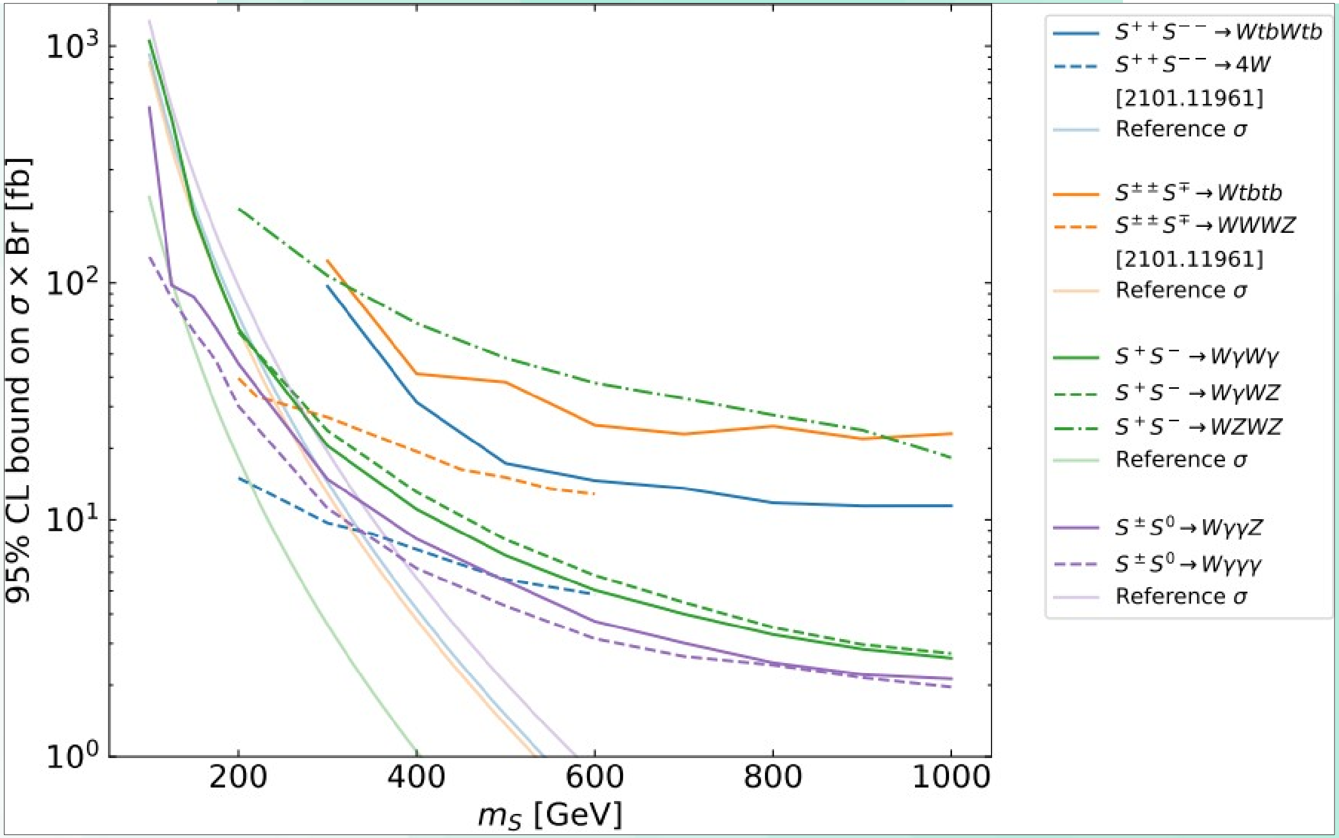


$$\left[\frac{i(\not{p} + M_{\mathcal{T}})}{(p^2 - M_{\mathcal{T}}^2)\mathbb{1} + iM_{\mathcal{T}}(\Gamma_{\mathcal{T}} + 2i\delta M)}\right]_{ij}$$

Search for exotic pNGBs



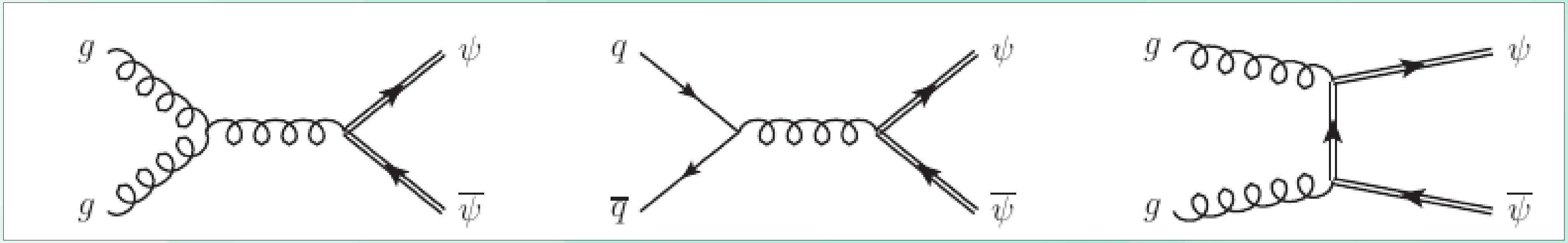


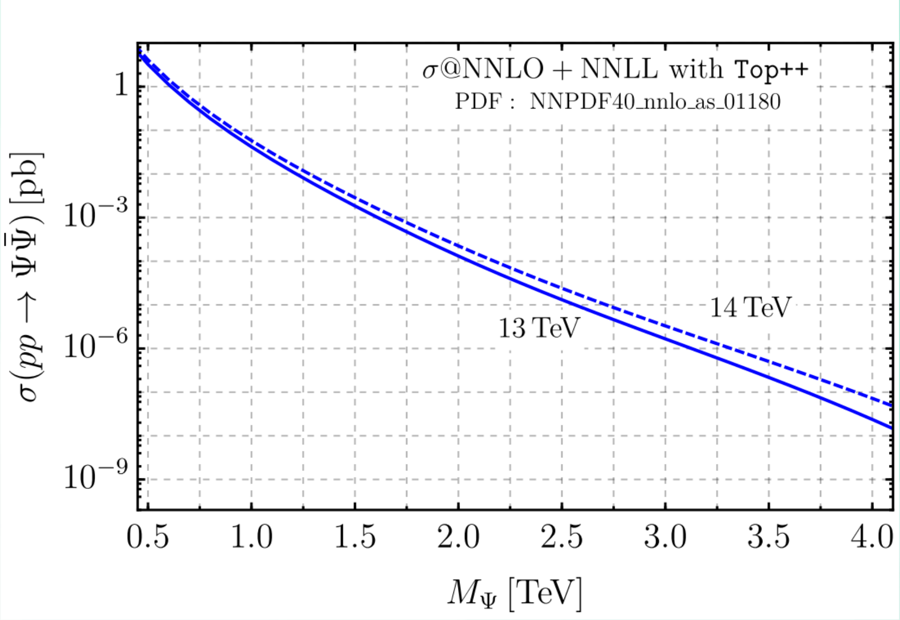


AB, D B Franzosi, G Cacciapaglia et. al.[2203.07270]

Production and decays of VLQs

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





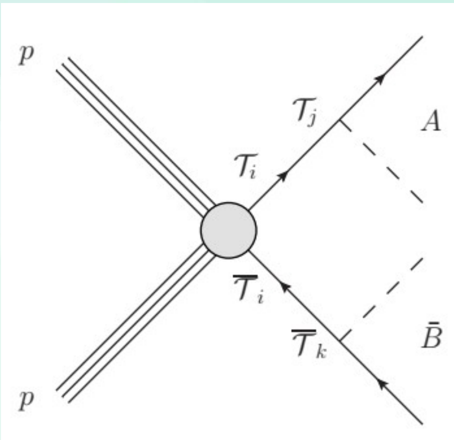
- **Possible decay channels**

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**

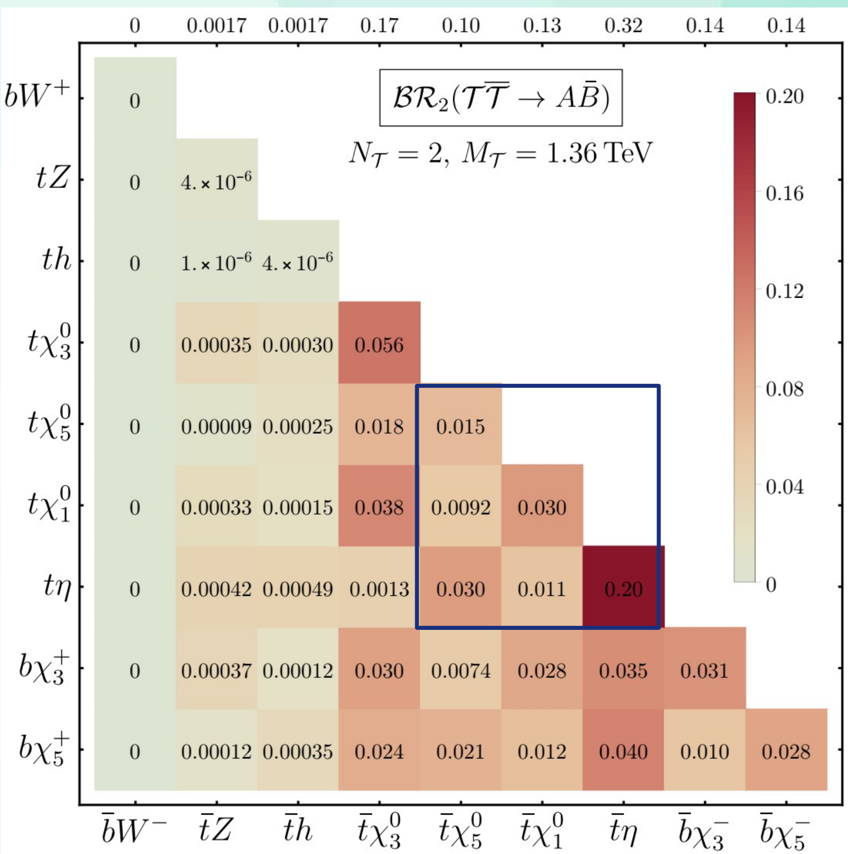
Decays of nearly degenerate states



- **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**



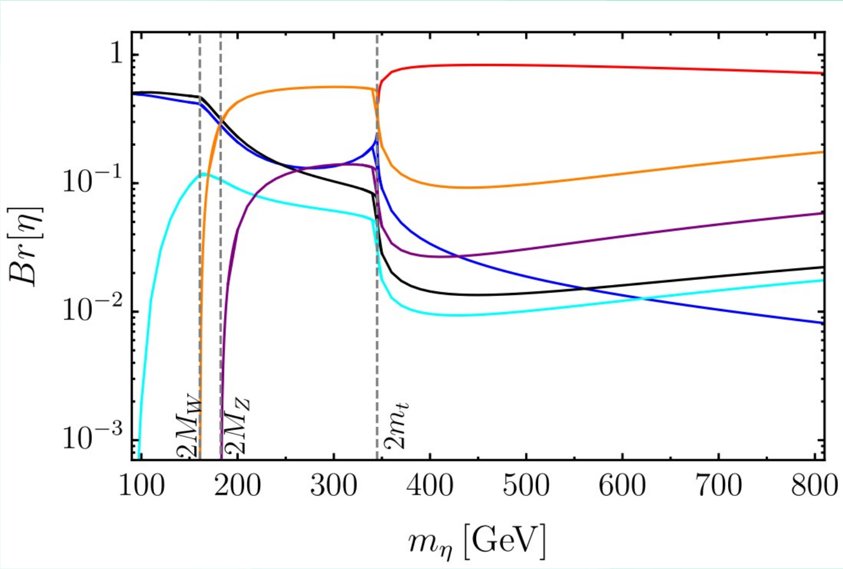
$$\sigma(pp \to \mathcal{T}\overline{\mathcal{T}} \to A\bar{B}) \overset{\text{NWA}}{=} N_{\mathcal{T}}\sigma(pp \to \mathcal{T}\overline{\mathcal{T}})\mathcal{BR}_2(\mathcal{T}\overline{\mathcal{T}} \to A\bar{B})$$

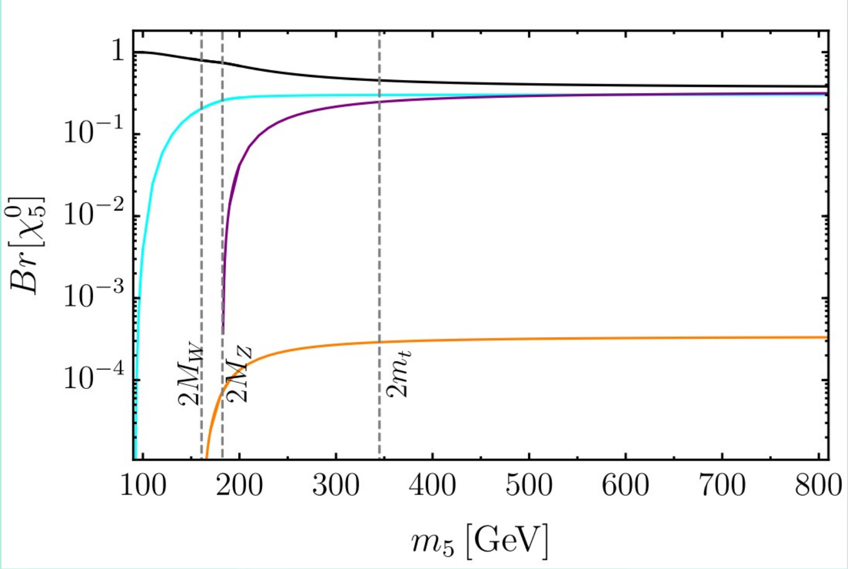
$$\mathcal{BR}(\mathcal{T} \to A) = \sum_{\bar{B}} \mathcal{BR}_2(\mathcal{T}\overline{\mathcal{T}} \to A\bar{B}) \qquad \sum_{A} \mathcal{BR}(\mathcal{T} \to A) = 1$$

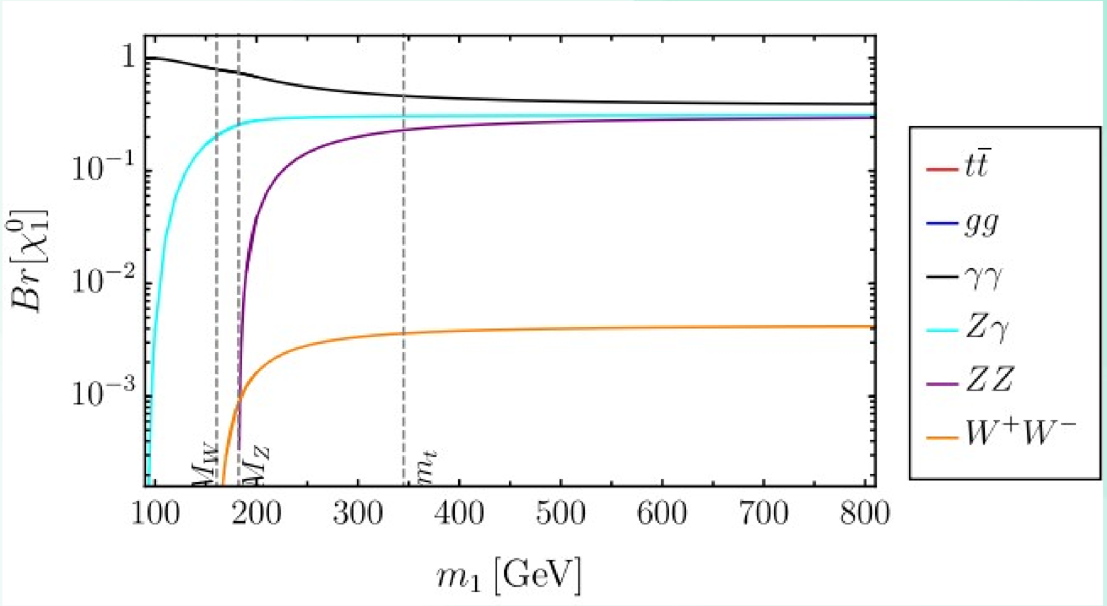
$$\mathcal{BR}_2(\mathcal{T}\overline{\mathcal{T}} \to A\bar{B}) \neq \mathcal{BR}(\mathcal{T} \to A)\mathcal{BR}(\bar{\mathcal{T}} \to \bar{B})$$

[AB, D B Franzosi, G Ferretti 2202.00037]

Branching ratios of pNGBs

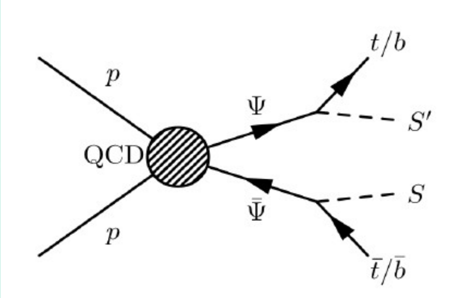






- **Decays into diboson are mainly driven by anomaly terms**
- χ_5^0 and χ_1^0 only decays via anomaly
- η decays to gg through top loop

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

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

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

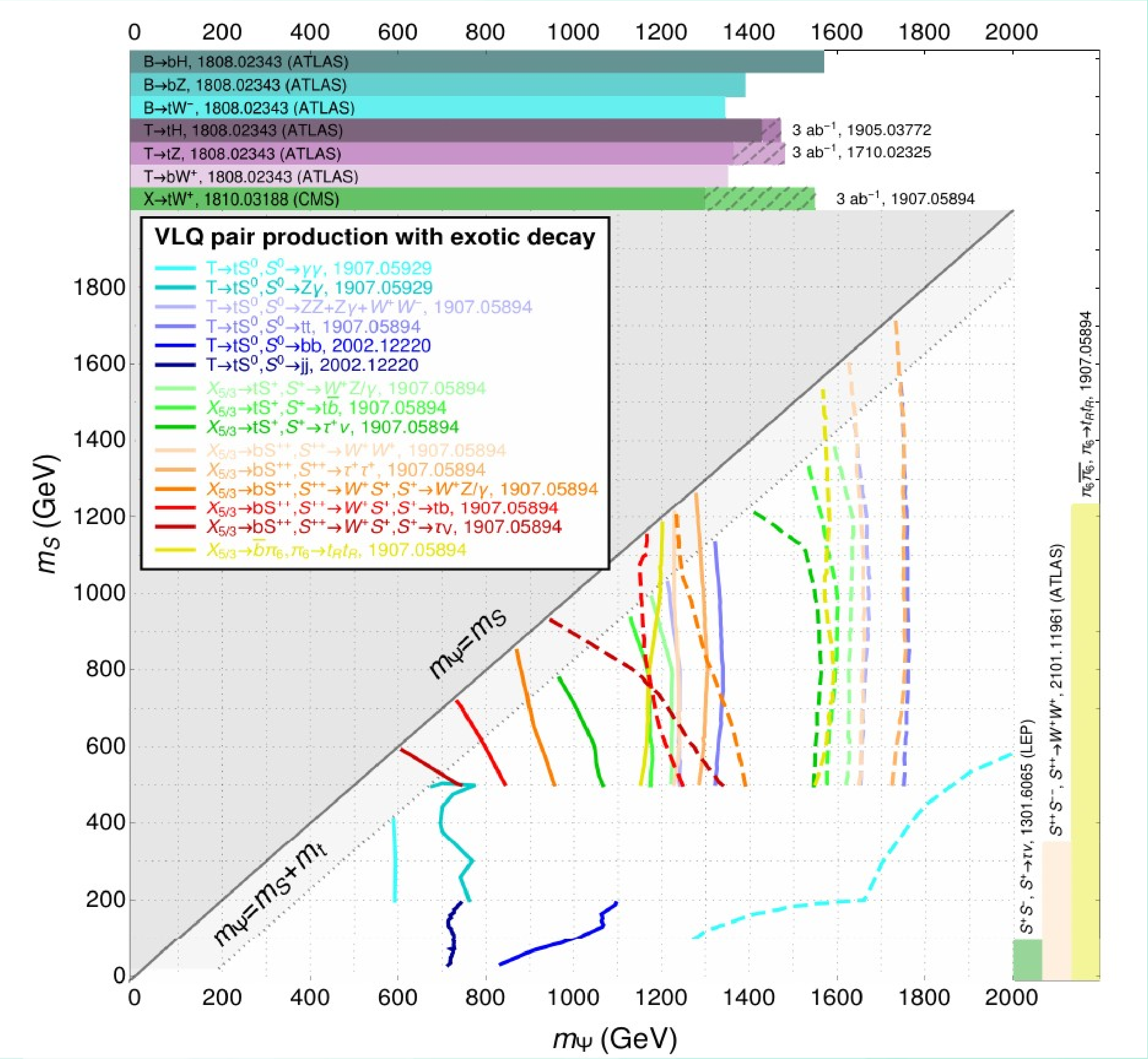
For hadronically decaying top):

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

More inclusive cross-sections involving diphoton (resonant / non-resonant) can go upto around 10 fb

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

Summary plot for VLQ search



AB, D B Franzosi, G Cacciapaglia et. al.[2203.07270]

Summary

- Composite pNGB Higgs from confining gauge theory: Major experimental signature arises from BSM pNGBs, colored VLQs and modifications in Higgs couplings.

- Higgs coupling measurements at LHC Run 2 put a bound on f around a TeV. Further exploration of differential distributions are needed to probe momentum dependent couplings.

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

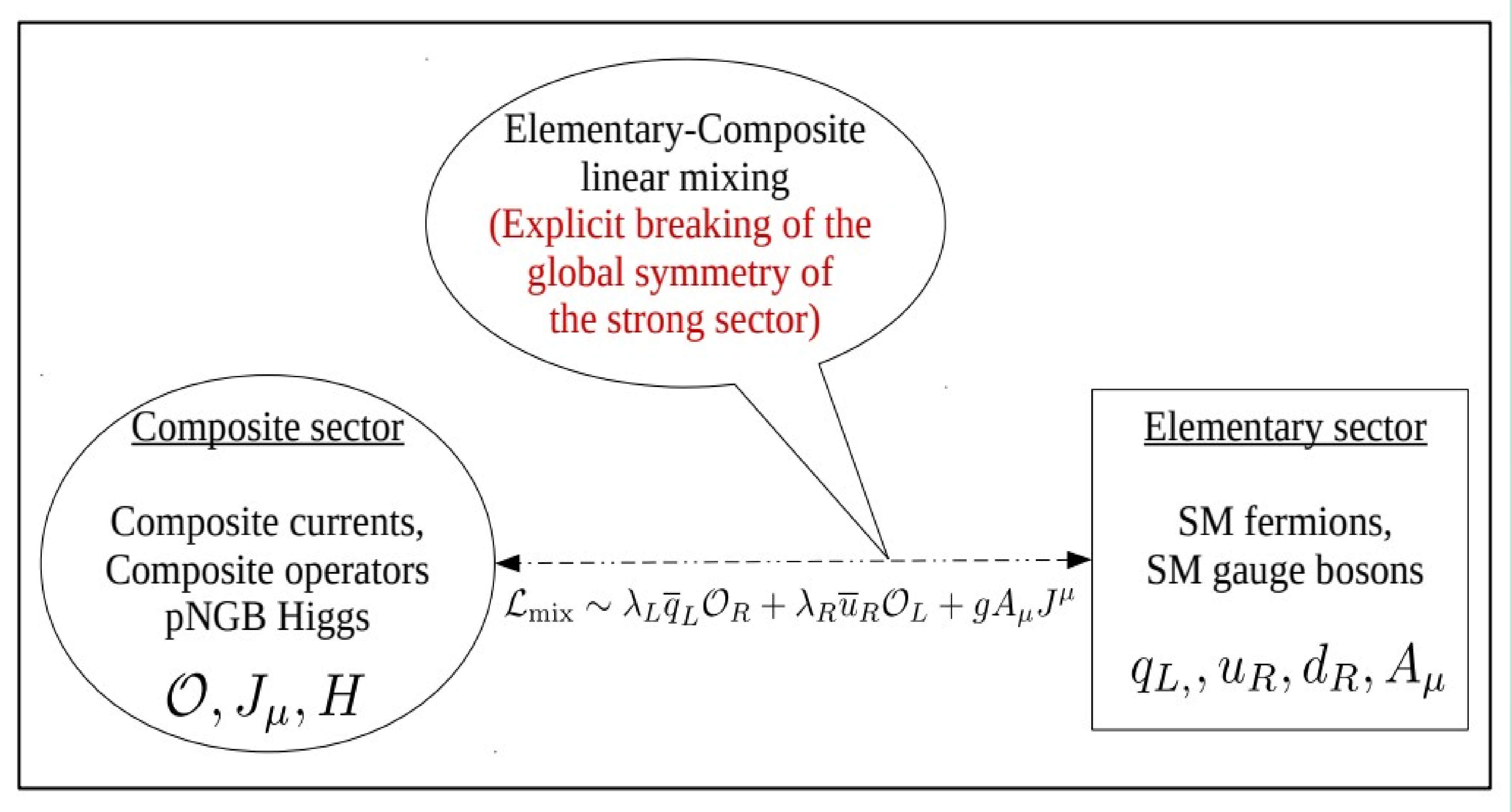
- Motivated models lead to interesting non-standard search topologies involving VLQs decaying into BSM pNGBs, followed by pNGBs decaying to diboson.

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

Thank you!

Backup

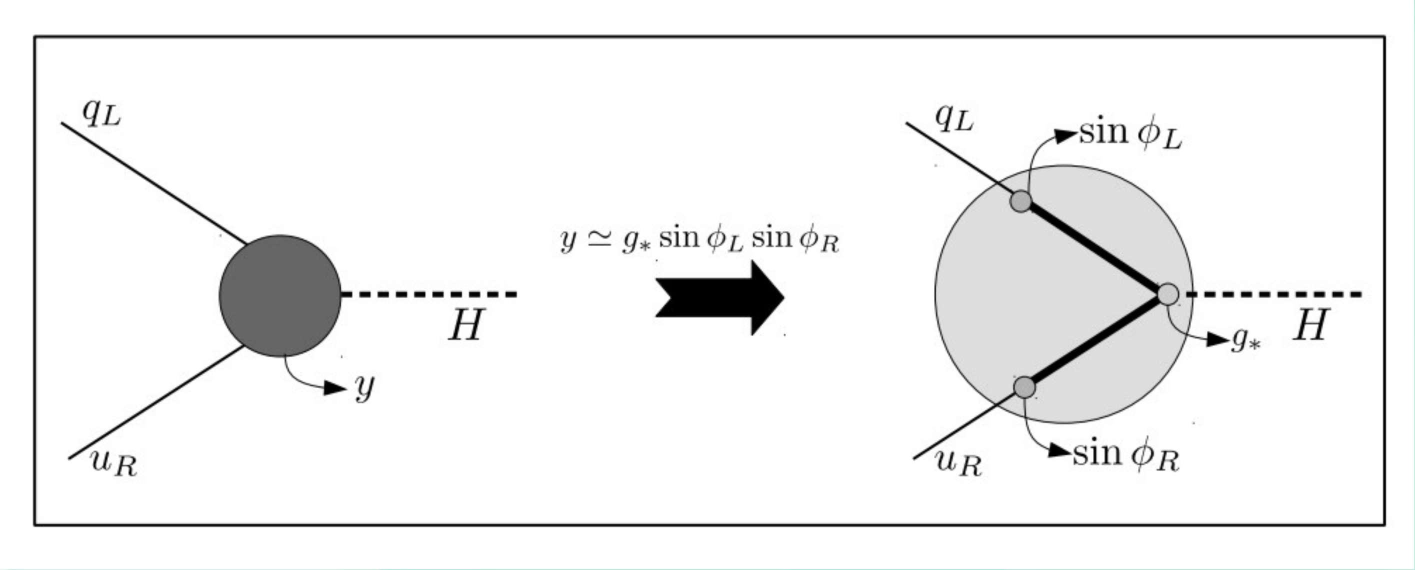
Partial compositeness



Physical states are linear combination of elementary and composite states

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

Yukawa couplings



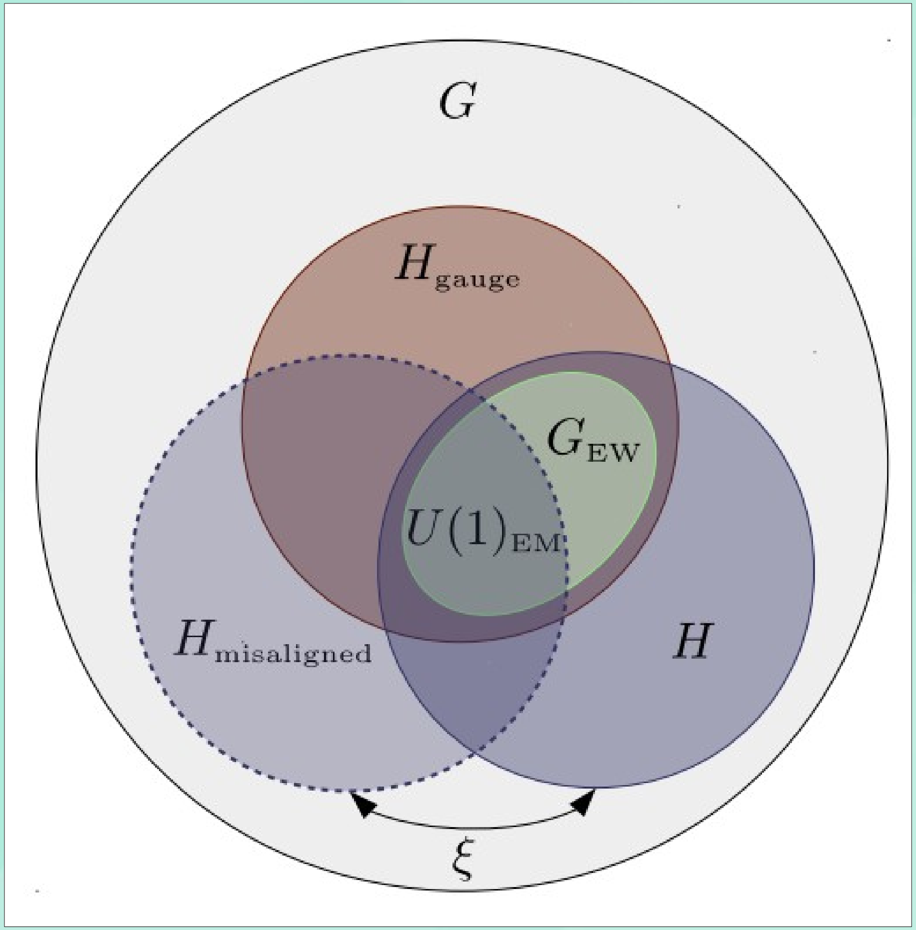
- **SM fermions : massive after EWSB**

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

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

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**

Coleman-Weinberg Higgs potential

$$V_{\text{top}}(h) = -2N_c \int \frac{d^4q_E}{(2\pi)^4} \log\left[-q_E^2\left(\Pi_0^L + \frac{\Pi_1^L}{2}s_h^2\right)\left(\Pi_0^R + \Pi_1^R c_h^2\right) - \frac{|\Pi_1^{LR}|^2}{2}s_h^2 c_h^2\right]$$

$$V_{\text{gauge}}(h) = \frac{9}{2}\int \frac{d^4q_E}{(2\pi)^4}\log\left[1 + \frac{\Pi_1(-q_E^2)}{4\Pi_0(-q_E^2)}s_h^2\right]$$

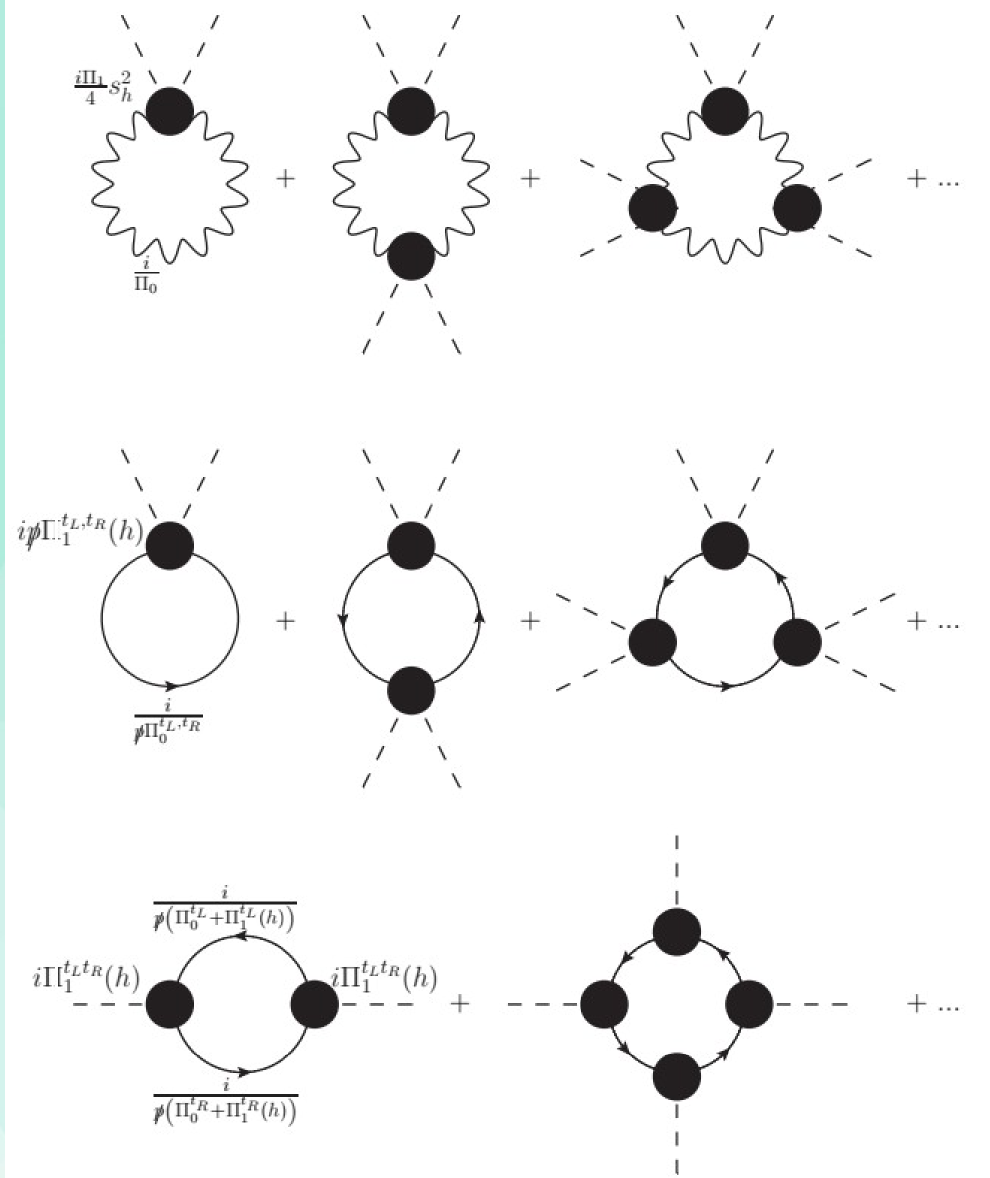
$$\simeq \frac{9}{2}\int \frac{d^4q_E}{(2\pi)^4}\left[\frac{\Pi_1}{4\Pi_0}s_h^2 - \frac{\Pi_1^2}{32\Pi_0^2}s_h^4\right]$$

$$V_{\text{eff}} = \alpha s_h^2 + \beta s_h^4$$

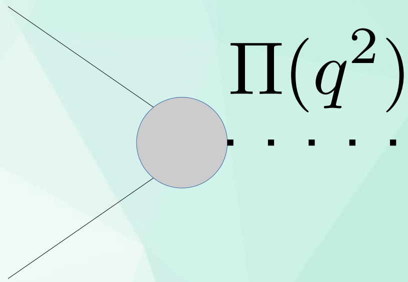
$\alpha_g > 0$ **Gauge contribution can not misalign the vacuum**

$\alpha_t < 0$ **Top contribution essential for EWSB**

$$\xi \equiv \langle s_h \rangle^2 = \frac{\alpha}{2\beta} \qquad m_h^2 = \frac{8}{f^2}\xi(1-\xi)\beta$$



Modified Higgs couplings



Form factors capturing strong dynamics

At low energy these can be described by higher-dim operators

$$\Delta\mathcal{L} \sim \frac{1}{2f^2}\partial_\mu(H^\dagger H)\partial^\mu(H^\dagger H) - \sum_{i=u,d}\Delta'_i y_i \frac{H^\dagger H}{f^2}\bar{q}_{L_i} H \psi_{R_i}$$

Dimension-6 operators due to pNGB nature of Higgs

'Model independent' phenomenological Lagrangian (Higgs chiral Lagrangian):

$$\mathcal{L}_{(0)} = \frac{h}{v}\left[k_V\left(2M_W^2 W_\mu^\dagger W^\mu + M_Z^2 Z_\mu Z^\mu\right) - \sum_f k_f m_f \bar{f} f\right]$$

$$\mathcal{L}_{(2)} = -\frac{h}{4\pi v}\left[\alpha_e k_{\gamma\gamma} F_{\mu\nu}F^{\mu\nu} + \alpha_e k_{Z\gamma} Z_{\mu\nu}F^{\mu\nu} - \frac{\alpha_s}{2} k_{gg} G^a_{\mu\nu} G^{a\mu\nu}\right]$$

Back to composite Higgs

hVV **Coupling modifier:** $k_V = \frac{g_{hVV}}{g_{hVV}^{SM}} = \sqrt{1-\xi}$ **(Universal, depends only on** ξ**)**

Yukawa coupling modifiers:

Top quark in fundamental 5 of SO(5): Single Yukawa operator

$$\mathcal{L}_{\text{Yuk}} = \Pi_{LR}(q^2)(\overline{Q}_L^5.\Sigma)(\Sigma^T.T_R^5) + \text{h.c.} = \Pi_{LR}(q^2)s_h c_h \bar{t}_L t_R + \text{h.c.} \quad \Longrightarrow \quad k_t = \frac{1-2\xi}{\sqrt{1-\xi}}$$

Top quark in symmetric 14 of SO(5):
Two Yukawa operators

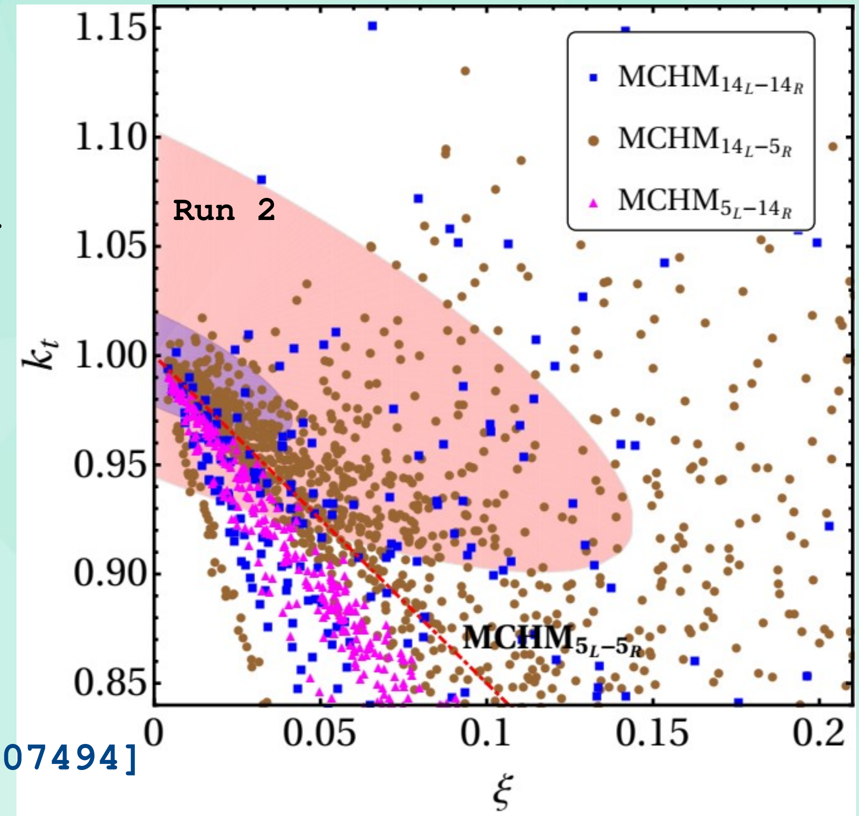
$$\mathcal{L}_{\text{Yuk}} = \Pi_{LR}^{(1)}(\Sigma^T.\overline{Q}_L^{14}.T_R^{14}.\Sigma) + \Pi_{LR}^{(2)}(\Sigma^T.\overline{Q}_L^{14}.\Sigma)(\Sigma^T.T_R^{14}.\Sigma) + \text{h.c.}$$

$$\Longrightarrow \quad k_t = 1 - \left[2\frac{\Pi_{LR}^{(2)}}{\Pi_{LR}^{(1)}} - \frac{3}{2}\right]\xi \equiv 1 + \Delta_t \xi$$

LHC Limits at 95% CL:

f >1.2 TeV (MCHM5)

f > 660 GeV (most conservative)



AB, G Bhattacharyya, N Kumar, T S Ray (JHEP)[1712.07494]

Custodial symmetry

- **Custodial symmetry** ➡ $\mathrm{SU}(2)_\mathrm{L} \times \mathrm{SU}(2)_\mathrm{R} \to \mathrm{SU}(2)_\mathrm{V}$

$$\rho_\mathrm{tree} = \frac{M_W^2}{M_Z^2 \cos\theta_w^2} = \frac{\sum_i v_i^2 \left[4T_i(T_i+1) - Y_i^2\right]}{\sum_i 2 v_i^2 Y_i^2}$$

One doublet

One doublet + singlets

Multi doublets

$$\rho_\mathrm{tree} = 1$$

$$\rho_\mathrm{exp} = 1.00039 \pm 0.00019$$

One doublet + one triplet

$$\rho_\mathrm{tree} \simeq 1 \pm \frac{2v_t^2}{v_d^2} \implies v_t < 1\ \mathrm{GeV}$$

Georgi-Machacek model

- **Doublet + one triplet ➡ Custodial symmetry violation**

$$\rho_{\rm tree} = \frac{M_W^2}{M_Z^2 \cos\theta_w^2} \simeq 1 \pm \frac{2v_t^2}{v_d^2} \quad \Longrightarrow \quad v_t \lesssim 1\mathrm{GeV}$$

- **Restore custodial symmetry: bidoublet + bitriplet**

$$\mathrm{SU(2)_L \times SU(2)_R} \quad \to \quad \mathrm{SU(2)_V}$$

$$\Phi = \begin{pmatrix} \phi^{0*} & \phi^+ \\ -\phi^- & \phi^0 \end{pmatrix} \qquad (\mathbf{2},\mathbf{2}) \quad \to \quad \mathbf{1} + \mathbf{3}$$

$$\Delta = \begin{pmatrix} \chi^{0*} & \xi^+ & \chi^{++} \\ -\chi^- & \xi^0 & \chi^+ \\ \chi^{--} & -\xi^- & \chi^0 \end{pmatrix} (\mathbf{3},\mathbf{3}) \quad \to \quad \mathbf{1} + \mathbf{3} + \mathbf{5}$$

$$\begin{pmatrix} h \\ H \end{pmatrix} \quad \begin{pmatrix} G^\pm \\ G^0 \end{pmatrix} \quad \begin{pmatrix} H_3^\pm \\ H_3^0 \end{pmatrix} \quad \begin{pmatrix} H_5^{\pm\pm} \\ H_5^\pm \\ H_5^0 \end{pmatrix}$$

$$\rho_{\rm tree} = \frac{2\langle\xi^0\rangle^2 + 2\langle\chi^0\rangle^2 + \langle\phi^0\rangle^2}{4\langle\chi^0\rangle^2 + \langle\phi^0\rangle^2} = 1$$

Georgi-Machacek model

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:

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

Vector-like quarks:

$$j^\mu = j^\mu_L + j^\mu_R = \bar{f}_L \gamma^\mu f'_L + \bar{f}_R \gamma^\mu f'_R = \bar{f} \gamma^\mu f'$$ **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