Precision observables of compositeness

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Dynamical electroweak symmetry breaking

Many attractive features

- ✓ **EWSB is triggered by a new strongly-coupled dynamics**
  more than one confinement scale in Nature? Higgs mechanism is effective?

- ✓ **No fundamental scalars**
  composite Higgs? Higgs "partners"?

- ✓ **No hierarchy problem, no fine-tuning**
  a best alternative to SUSY with fewer free parameters?

- ✓ **A plenty of new hadron-like objects, difficult to find/treat though**
  composite Dark Matter? LHC phenomenology? ..etc

Evolutions of DEWSB ideas/realizations

Technicolor

Extended TC

Walking TC

Bosonic TC

Composite Higgs EFT's
e.g. MCHM SO(5)/SO(4)

???

Hill & Simmons, Phys. Rept. 381, 235 (2003)
Sannino, Acta Phys. Polon. B40, 3533 (2009), etc

No consistent UV completion has yet been proposed….

A new energy scale from confinement?

Well-known example: QCD at low momentum scales

QCD
$\Lambda_{\rm QCD} \sim 200$ MeV

Static properties of light hadrons can be completely determined by two dimensionful vacuum parameters:

gluon condensate:

$$\langle 0|\frac{\alpha_s}{\pi}\hat{G}_{\mu\nu}\hat{G}^{\mu\nu}|0\rangle = (365 \pm 20\,{\rm MeV})^4 \simeq (2\Lambda_{\rm QCD})^4\,,$$

light quark condensate:

$$\langle 0|\bar{u}u|0\rangle = \langle 0|\bar{d}d|0\rangle = -l_g\langle 0|\frac{\alpha_s}{\pi}\hat{G}_{\mu\nu}\hat{G}^{\mu\nu}|0\rangle = -(235 \pm 15\,{\rm MeV})^3$$

Simplistic approach: one employs a direct analogy with QCD

"T-QCD"
$\Lambda_{\rm TC} \gtrsim v \sim 200$ GeV

Spectrum of light composites (incl. Higgs) is governed by

$$\langle 0|\frac{\alpha_{\rm TC}}{\pi}\hat{F}_{\mu\nu}\hat{F}^{\mu\nu}|0\rangle \sim (2\Lambda_{\rm TC})^4\,,$$

$$\langle 0|\bar{U}U|0\rangle = \langle 0|\bar{D}D|0\rangle \sim -l_{\rm TC}(2\Lambda_{\rm TC})^4$$

working hypothesis:

The energy scale of both EW theory (SM) and new strongly-coupled dynamics has a common origin: the Tquark-Tgluon condensate

Issues of Technicolor: oblique corrections

New Physics must come in loops ⟹ *should not disturb EW obs too much!*

Peskin&Takeuchi PRL'90

Generic parameterization of NP effects is EW observables in terms of S,T,U parameters

$$M_Z^2 = M_{Z0}^2 \frac{1-\widehat{\alpha}(M_Z)T}{1-G_F M_{Z0}^2 S/2\sqrt{2}\pi}$$

$$M_W^2 = M_{W0}^2 \frac{1}{1-G_F M_{W0}^2 (S+U)/2\sqrt{2}\pi}$$

$$\Gamma_Z = \frac{M_Z^3 \beta_Z}{1-\widehat{\alpha}(M_Z)T}$$

PDG'13

Extra chiral heavy family doublet brings up

$$S = \frac{C}{3\pi}\sum_i \Big(t_{3L}(i) - t_{3R}(i)\Big)^2 \;=\; 2/3\pi$$

Standard QCD-like TC $S \sim 0.45$

EW precision constraints on New Physics

$$S = 0.00^{+0.11}_{-0.10} \qquad T = 0.02^{+0.11}_{-0.12} \qquad U = 0.08 \pm 0.11$$

vector SU(2) breaking (S) — **axial SU(2) breaking** (T, U)

Non-QCD-like (Walking) TC still survives but has other issues...

- *Flavour-Changing neutral-currents*
- *Too-light quarks*
- *Too many unobserved pseudo-Goldstone states*

Is a new QCD-like dynamics completely dead?

Vector-like weak interactions

Which confined symmetry enables to transform a chiral UV completion into a vector-like one?

RP et al, arXiv:1407.2392

$$SU(N_{\rm TC})_{\rm TC} \qquad \tilde{Q} = \begin{pmatrix} U \\ D \end{pmatrix}, \qquad Y_{\tilde{Q}} = \begin{cases} 0, & \text{if } N_{\rm TC} = 2\,, \\ 1/3, & \text{if } N_{\rm TC} = 3\,. \end{cases}$$

start with two generations of CHIRAL fields

$$SU(2)_{\rm W} \otimes SU(2)_{\rm TC}$$

$$A = 1,2$$

$$\tilde{Q}^{a\alpha'}_{L(A)} = \tilde{Q}^{a\alpha}_{L(A)} + \frac{i}{2} g_W \theta_k \tau_k^{ab} \tilde{Q}^{b\alpha}_{L(A)} + \frac{i}{2} g_{TC} \varphi_k \tau_k^{\alpha\beta} \tilde{Q}^{a\beta}_{L(A)}\,,$$

new R-handed WEAK DOUBLET

$$Q^{a\alpha}_{R(2)} \equiv \varepsilon^{ab} \varepsilon^{\alpha\beta} Q^{Cb\beta}_{L(2)}$$

charge conjugation of the SECOND generation

$$\hat{\rm C} Q^{a\alpha}_{L(2)} = Q^{Ca\alpha}_{L(2)}\,,$$

$$Q^{Ca\alpha'}_{L(2)} = Q^{Ca\alpha}_{L(2)} - \frac{i}{2} g_W \theta_k (\tau_k^{ab})^* Q^{Cb\alpha}_{L(2)} - \frac{i}{2} g_{TC} \varphi_k (\tau_k^{\alpha\beta})^* Q^{Ca\beta}_{L(2)}\,.$$

We end up Dirac WEAK DOUBLET

$$Q^{a\alpha} = Q^{a\alpha}_{L(1)} + Q^{a\alpha}_{R(2)}$$

At the fundamental level, we arrive at the simplest possible VLTC Lagrangian:

$$L_{\rm TC} = -\frac{1}{4} G_{\mu\nu} G^{\mu\nu} + i\bar{Q}\gamma^\mu \Big(\partial_\mu - \frac{iY_Q}{2} g' B_\mu - \frac{i}{2} g W_\mu^a \tau^a + \frac{i}{2} g_{\rm TC} G_\mu^a \lambda^a \Big) Q - m\bar{Q}Q$$

Toy-model of DEWSB: $SU(2)_L \times SU(2)_R$ LσM

LσM in QCD hadron physics: a model for constituent quark-meson interactions

T. Eguchi, Phys. Rev. D 14, 2755 (1976);
K. Kikkawa, Prog. Theor. Phys. 56, 947 (1976);
M. K. Volkov, Sov. J. Part. Nucl. **17**, 186 (1986)

the source term

$$-g_{\rm TC}\bar{Q}(S+i\gamma_5 P^a)Q \quad \rightarrow \quad -g_{\rm TC}\Big(\langle\bar{Q}Q\rangle S+\bar{Q}(S+i\gamma_5 P^a\tau^a)Q\Big)$$

scalar T-sigma (singlet rep.) — lightest T-glueball

pseudoscalar T-pions (adjoint rep.) — collective excitation of T-quark condensate

QGC formation

$$\bar{Q}Q \rightarrow \langle\bar{Q}Q\rangle + \bar{Q}Q$$

$$S = u + \sigma$$

T-pion mass

$$m_Q \ll m_\pi = -\frac{g_{\rm TC}\langle\bar{\tilde{Q}}\tilde{Q}\rangle}{u}$$

global chiral SSB

$$SU(2)_{\rm L}\otimes SU(2)_{\rm R} \rightarrow SU(2)_{\rm V\equiv L+R}$$

$$\mu_{\rm S,H} \ll m_{\tilde{\pi}}$$

Potential

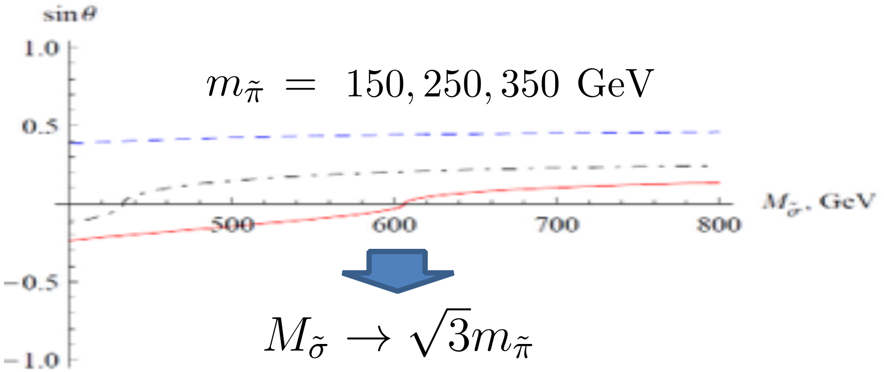
$$\frac{1}{2}\mu_{\rm S}^2(S^2+P^2)+\mu_{\rm H}^2\mathcal{H}^2-\frac{1}{4}\lambda_{\rm TC}(S^2+P^2)^2-\lambda_{\rm H}\mathcal{H}^4+\lambda\mathcal{H}^2(S^2+P^2)$$

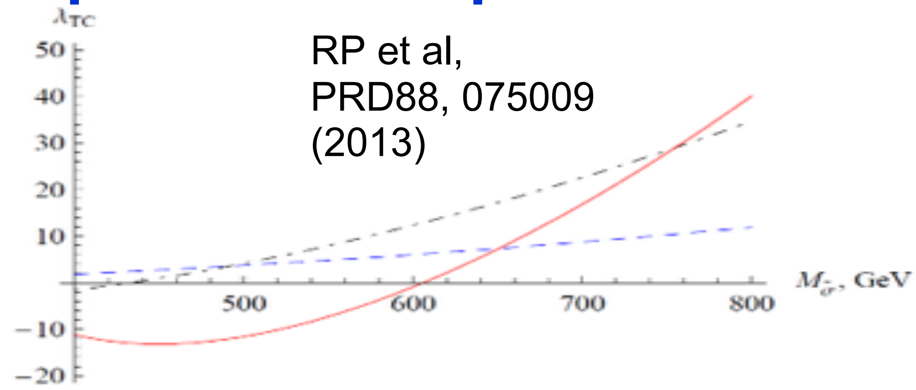
$$\langle\mathcal{H}\rangle = \frac{1}{\sqrt{2}}\begin{pmatrix}0\\ v\end{pmatrix} \qquad u=\left(\frac{\lambda_{\rm H}}{\delta}\right)^{1/3}\bar{g}_{\rm TC}^{1/3}\,, \qquad v=\left(\frac{\xi\lambda}{\lambda_{\rm H}}\right)^{1/2}\left(\frac{\lambda_{\rm H}}{\delta}\right)^{1/3}\bar{g}_{\rm TC}^{1/3}$$

Spontaneous EWSB

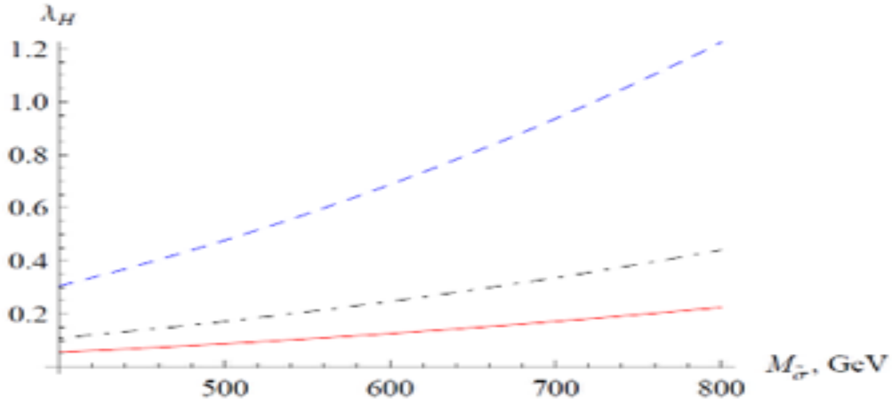
- *Both chiral and EW SSB are dynamically linked to T-quark condensate*
- *T-pion gets mass via T-sigma interaction with T-quark condensate*
- *T-pions remain physical, the Higgs-like mechanism becomes effective*

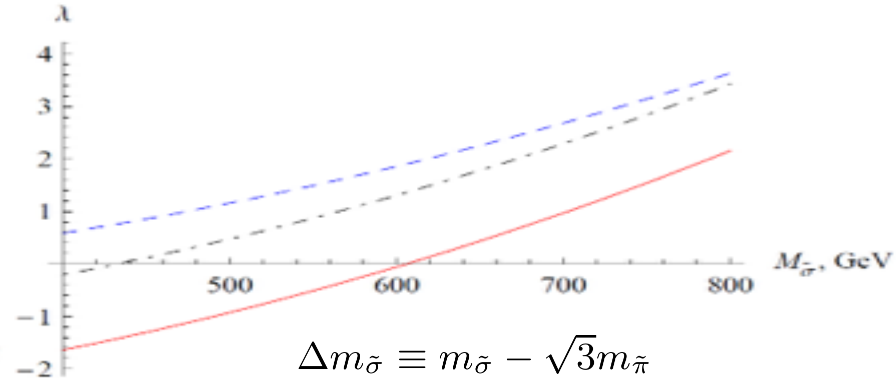
SU(2)LxSU(2)R: parameter space



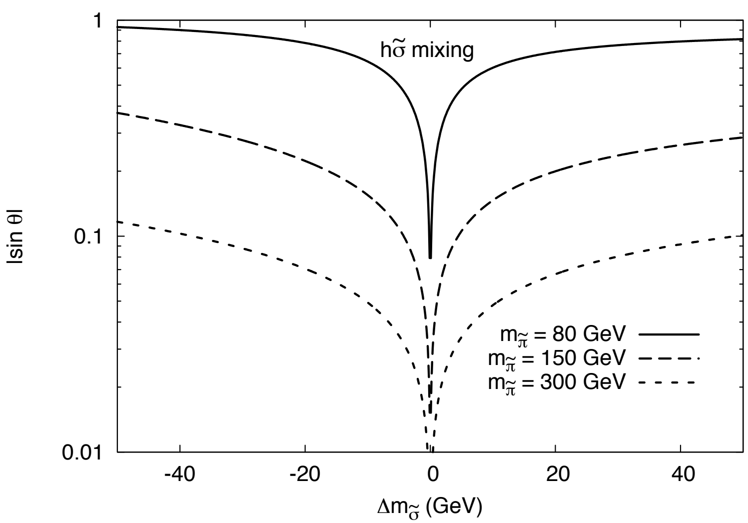


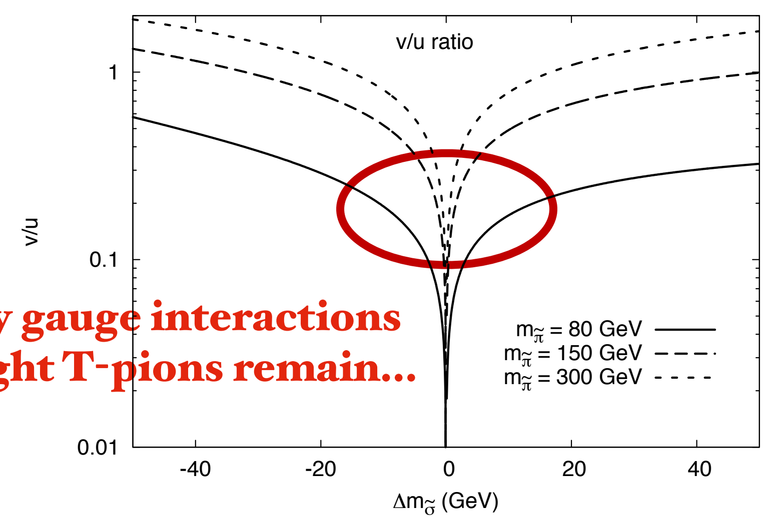
RP et al,
PRD88, 075009
(2013)





$\Delta m_{\tilde\sigma} \equiv m_{\tilde\sigma} - \sqrt{3} m_{\tilde\pi}$



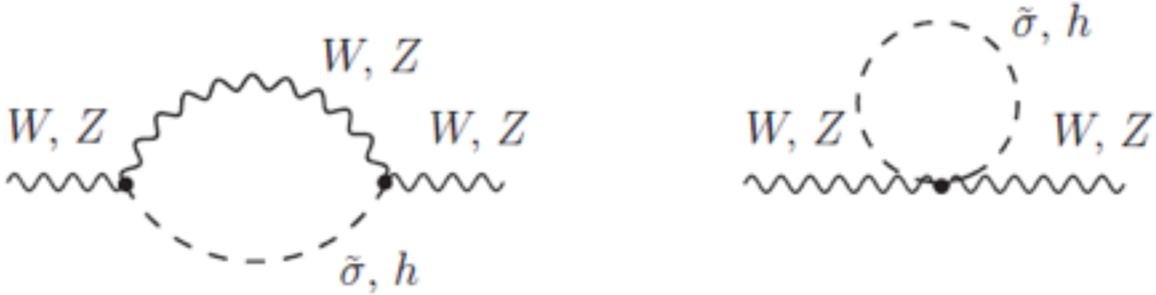


only gauge interactions of light T-pions remain…

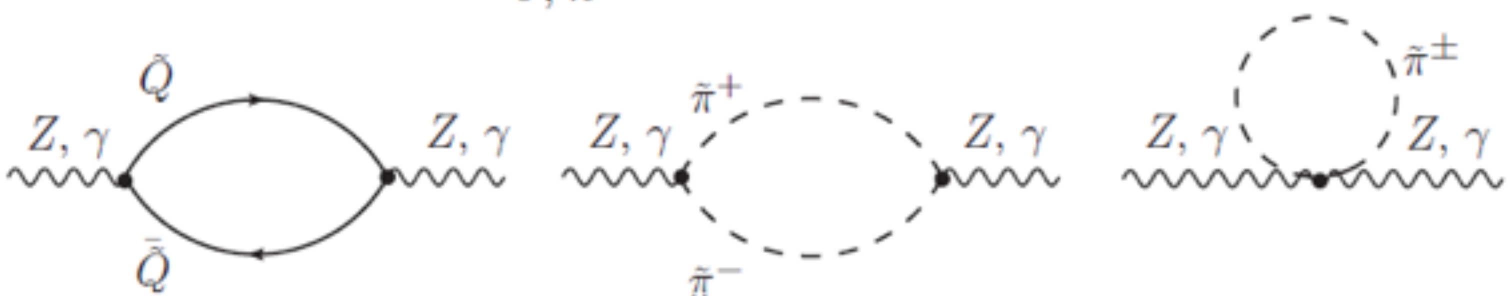
$SU(2)_L \times SU(2)_R$: oblique corrections

NEW!

Modified SM + T-sigma!



NEW!



$$\Pi^{\rm new}_{\rm XY}(q^2) = \Pi^{\tilde{\pi}}_{\rm XY}(q^2) + \Pi^{\tilde{Q}}_{\rm XY}(q^2) + \Pi^{\tilde{\sigma}}_{\rm XY}(q^2) \qquad \Pi^{\rm SM'}_{\rm XY}(q^2) = \Pi^{h}_{\rm XY}(q^2)$$

T-pion and Dirac T-quark contributions

RP et al, PRD88, 075009 (2013)

$$\delta\Pi_{XY}(q^2) = \delta\Pi^{sc}_{XY}(q^2) + \Pi^{\tilde{\pi}}_{XY}(q^2, m^2_{\tilde{\pi}}) + \Pi^{\tilde{Q}}_{XY}(q^2, M^2_{\tilde{Q}})$$

can be large in the T-parameter only!

give vanishing contributions to all oblique corrections for any VLTC parameters!

T-pion/T-quark loops

$$\Pi^{\tilde{\pi}}_{XY}(q^2, m^2_{\tilde{\pi}}) = \frac{g^2}{24\pi^2} K_{XY}\, F_{\tilde{\pi}}(q^2, m^2_{\tilde{\pi}})\,, \quad \Pi^{\tilde{Q}}_{XY}(q^2, M^2_{\tilde{Q}}) = \frac{g^2 N_c}{24\pi^2} K_{XY}\, \kappa_{XY}\, F_{\tilde{Q}}(q^2, M^2_{\tilde{Q}})$$

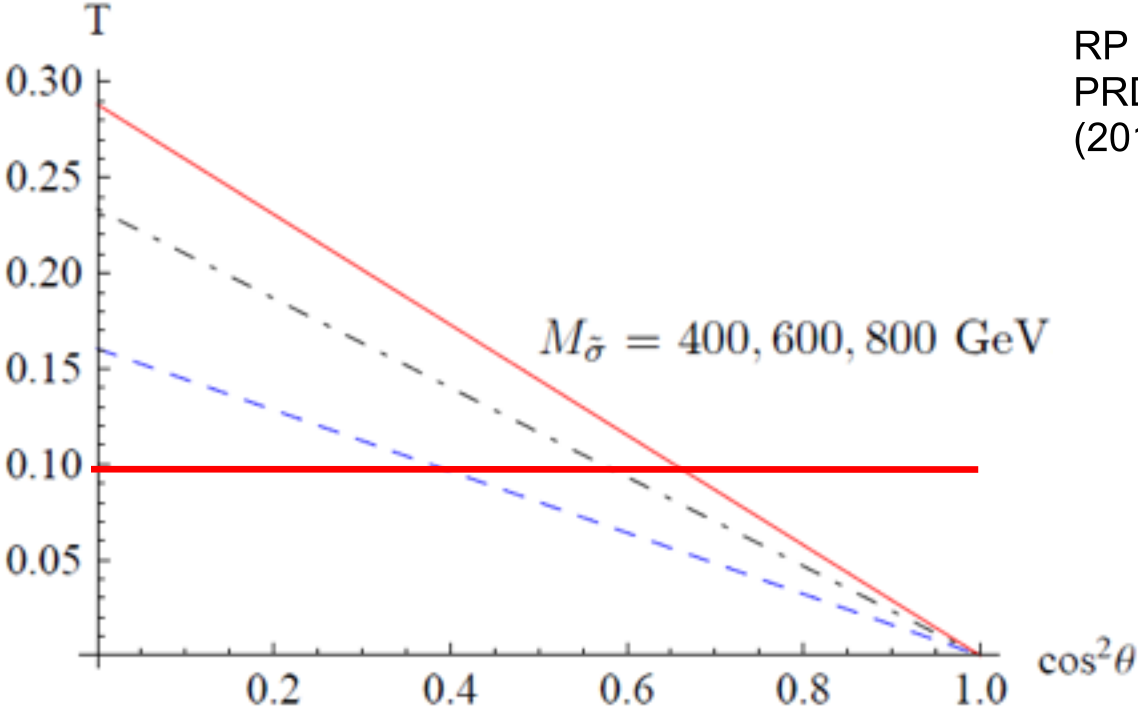
$$F_{\tilde{\pi}}(0, m^2_{\tilde{\pi}}) = 0 \qquad F_{\tilde{Q}}(0, M^2_{\tilde{Q}}) = 0 \quad \Rightarrow \quad T^{\tilde{\pi}} = T^{\tilde{Q}} = 0$$

$$Y_{\tilde{Q}} = 0 \quad \Rightarrow \quad \begin{aligned} \frac{\alpha\, S^{\tilde{\pi}+\tilde{Q}}}{4 s_W^2 c_W^2} &= f(M_Z^2, m^2_{\tilde{\pi}}, M^2_{\tilde{Q}}) \cdot \left[c_W^2 - \frac{c_W^2 - s_W^2}{c_W s_W} \cdot c_W s_W - s_W^2 \right] = 0 \\ \frac{\alpha\, U^{\tilde{\pi}+\tilde{Q}}}{4 s_W^2} &= f(M_Z^2, m^2_{\tilde{\pi}}, M^2_{\tilde{Q}}) \cdot \left[1 - c_W^4 - s_W^4 - 2 c_W^2 s_W^2 \right] = 0\,, \end{aligned}$$

Vector-like weak interactions of the UV completion preserve Technicolor!

T-parameter: constraint on σh-mixing and σ-mass

RP et al,
PRD88, 075009
(2013)

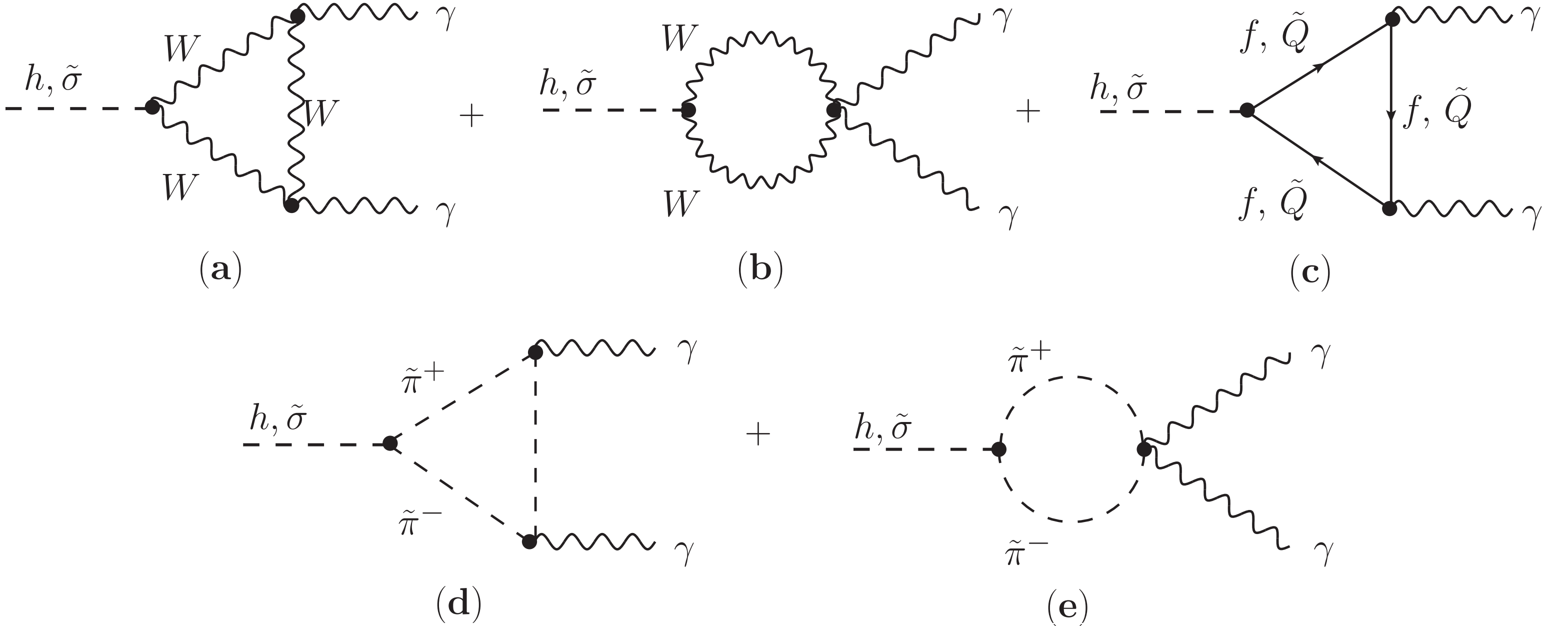


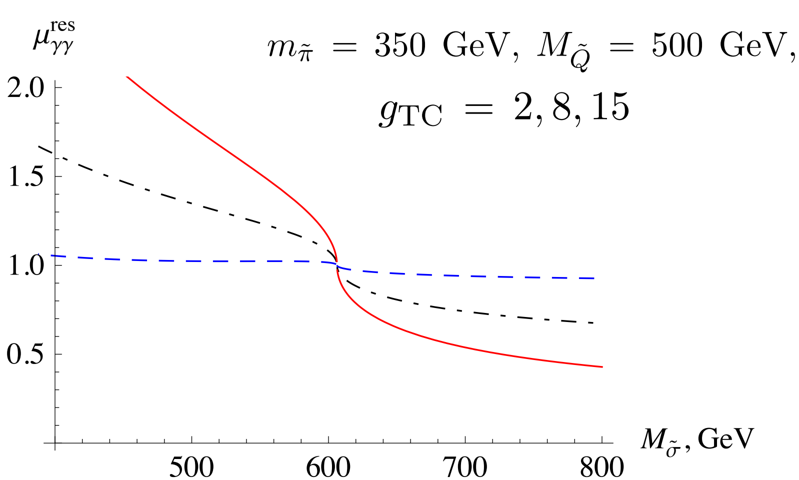
a small mixing angle and/or small σ-mass are preferable!

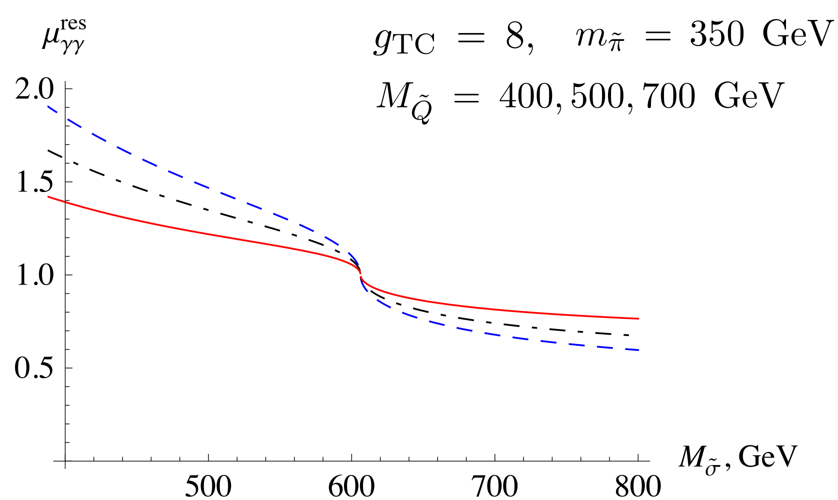
Given by **scalar contribution** **ONLY**

$$
\begin{aligned}
\delta\Pi^{sc}_{\rm XY}(q^2) &= \Pi^{\tilde{\sigma}}_{\rm XY}(q^2, M^2_{\tilde{\sigma}}) + \Pi^{h}_{\rm XY}(q^2, M^2_{h}) - \Pi^{SM,h}_{\rm XY}(q^2, M^2_{h}) \\
&= s^2_\theta\, \Pi^{\rm SM,h}_{\rm XY}(q^2, M^2_{\tilde{\sigma}}) - s^2_\theta\, \Pi^{\rm SM,h}_{\rm XY}(q^2, M^2_{h}) \,.
\end{aligned}
$$

SU(2)LxSU(2)R: Higgs signal rates

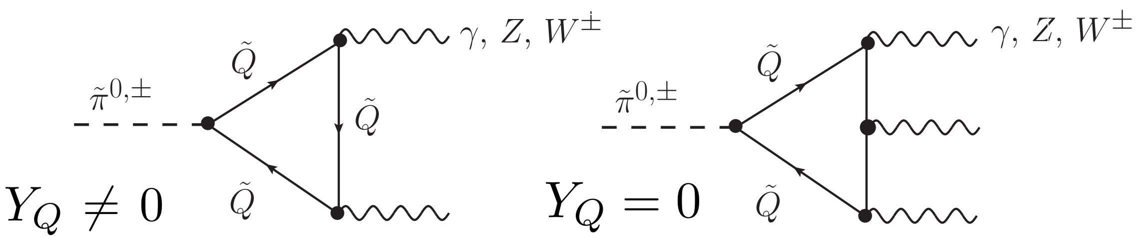


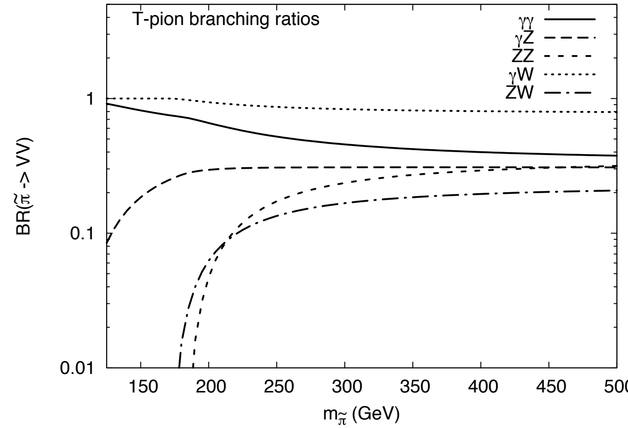




SU(2)LxSU(2)R: search for T-pions

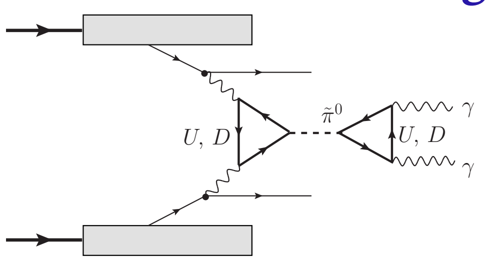
T-pion decay

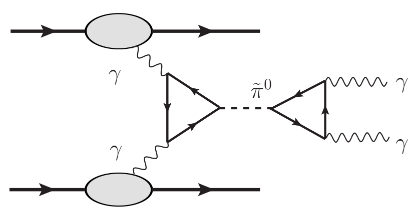




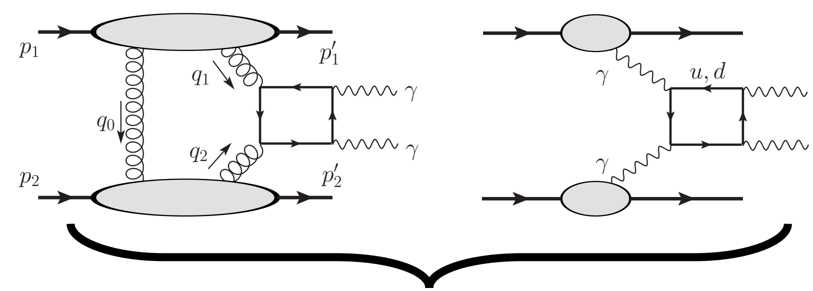
RP et al,
NP881, 288 (2014)

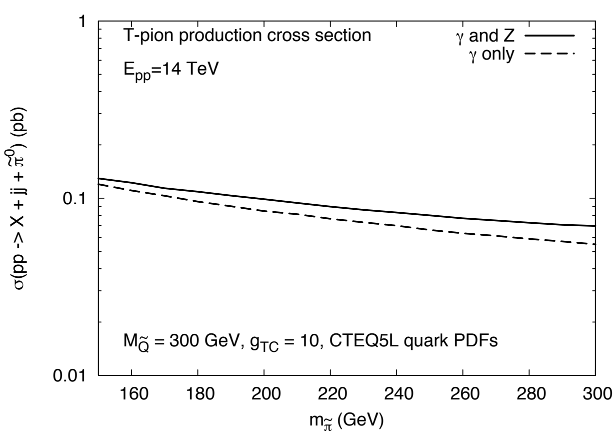
Signal

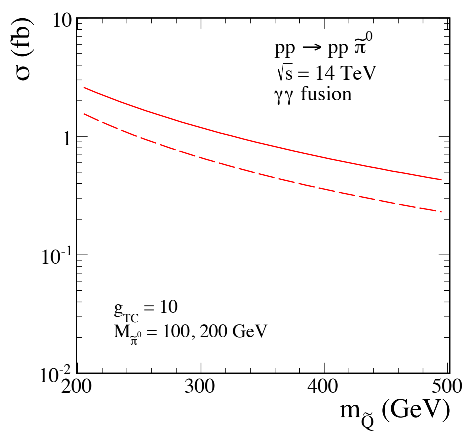


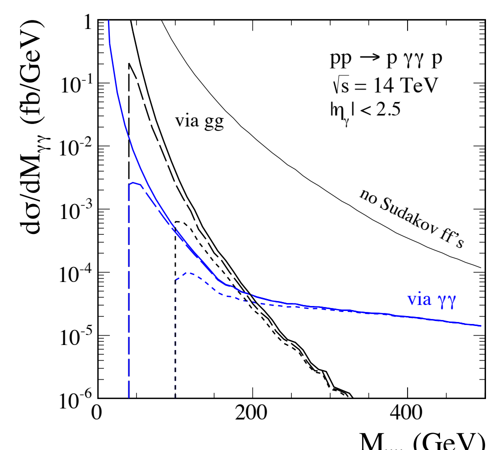


Background









SU(3)LxSU(3)R composite Higgs model: content

$\mathcal{Q}_L = (U, D, S)_L \qquad \mathcal{Q}_R = (U, D, S)_R$

chiral → Dirac T-quarks in SU(2)TC

Fundamental Lagrangian

$$L_{TC} = -\frac{1}{4}T^n_{\mu\nu}T^{\mu\nu}_n + i\bar{Q}\gamma^\mu\left(\partial_\mu - \frac{i}{2}g_W W^A_\mu \tau_A - \frac{i}{2}g_{TC}T^n_\mu \tau_n\right)Q - m_Q\bar{Q}Q +$$

$$+i\bar{S}\gamma^\mu\left(\partial_\mu + \frac{i}{2}g_1 B_\mu - \frac{i}{2}g_{TC}T^n_\mu\tau_n\right)S - m_S\bar{S}S$$

pseudo-Goldstones: $\pi^+, \pi^0, \pi^-; \quad K^+, K^0, \bar{K}^0, K^-; \quad \eta$

their chiral partners: $a^+, a^0, a^-; \quad H^+, H^0, \bar{H}^0, H^-; \quad f$

$+ \quad \sigma \quad \eta'$

components of the bi-fundamental rep:

$$\hat{\Phi} = \frac{1}{\sqrt{2}}\begin{pmatrix} \frac{1}{\sqrt{2}}a^0 + \frac{1}{\sqrt{6}}f + \frac{1}{\sqrt{3}}\sigma & a^+ & H^+ \\ a^- & -\frac{1}{\sqrt{2}}a^0 + \frac{1}{\sqrt{6}}f + \frac{1}{\sqrt{3}}\sigma & H^0 \\ H^- & \bar{H}^0 & -\sqrt{\frac{2}{3}}f + \frac{1}{\sqrt{3}}\sigma \end{pmatrix} -$$

$$-\frac{i}{\sqrt{2}}\begin{pmatrix} \frac{1}{\sqrt{2}}\pi^0 + \frac{1}{\sqrt{6}}\eta + \frac{1}{\sqrt{3}}\eta' & \pi^+ & K^+ \\ \pi^- & -\frac{1}{\sqrt{2}}\pi^0 + \frac{1}{\sqrt{6}}\eta + \frac{1}{\sqrt{3}}\eta' & K^0 \\ K^- & \bar{K}^0 & -\sqrt{\frac{2}{3}}\eta + \frac{1}{\sqrt{3}}\eta' \end{pmatrix}$$

Generic global LσM Lagrangian:

$$L_\sigma = i\bar{\mathcal{Q}}\gamma^\mu\partial_\mu\mathcal{Q} - \sqrt{6}\varkappa(\bar{\mathcal{Q}}_L\Phi\mathcal{Q}_R + \bar{\mathcal{Q}}_R\Phi^+\mathcal{Q}_L) + \partial_\mu\hat{\Phi}^+\cdot\partial^\mu\hat{\Phi} +$$

$$+\mu^2\hat{\Phi}^+\hat{\Phi} - \lambda_1(\hat{\Phi}^+\hat{\Phi})^2 - 3\lambda_2\hat{\Phi}^+\hat{\Phi}\hat{\Phi}^+\hat{\Phi} + 2\sqrt{6}\Lambda_3\mathrm{Re}\,\det\Phi\ .$$

SU(3)LxSU(3)R CHM: EW interactions of composites

Additional EW-invariant piece to the Higgs-less SM Lagrangian:

$$L_\sigma = i\bar{Q}\gamma^\mu \left(\partial_\mu - \frac{i}{2} g_W W^a_\mu \tau_a\right) Q + i\bar{S}\gamma^\mu \left(\partial_\mu + \frac{i}{2} g_1 B_\mu\right) S - \sqrt{6}\varkappa(\bar{\mathcal{Q}}_L \Phi \mathcal{Q}_R + \bar{\mathcal{Q}}_R \Phi^+ \mathcal{Q}_L) +$$

$$\frac{1}{2}(D^\mu \pi_a \cdot D_\mu \pi_a + D^\mu a_a \cdot D_\mu a_a) + (D^\mu K)^+ \cdot D_\mu K + (D^\mu H)^+ \cdot D_\mu H +$$

composite Higgs-like kinetic terms

$$\frac{1}{2}(\partial_\mu \eta \cdot \partial^\mu \eta + \partial_\mu \eta_0 \cdot \partial^\mu \eta_0 + \partial_\mu f \cdot \partial^\mu f + \partial_\mu \sigma \cdot \partial^\mu \sigma) +$$

$$\mu^2 \hat{\Phi}^+ \hat{\Phi} - \lambda_1 (\hat{\Phi}^+ \hat{\Phi})^2 - 3\lambda_2 \hat{\Phi}^+ \hat{\Phi} \hat{\Phi}^+ \hat{\Phi} + 2\sqrt{6}\Lambda_3 \mathrm{Re}\,\det\Phi -$$

replaces Higgs potential

$$(Y^l_{mn} \bar{L}_m H E_n + Y^d_{mn} \bar{Q}_m H D_n + Y^u_{mn} \bar{Q}_m \tilde{H} U_n + h.c.) -$$

$$(\overline{Y}^l_{mn} \bar{L}_m K E_n + \overline{Y}^d_{mn} \bar{Q}_m K D_n + \overline{Y}^u_{mn} \bar{Q}_m \tilde{K} U_n + h.c.)\ ,$$

to be constrained by FCNC etc

where

$$D_\mu \pi_a = \partial_\mu \pi_a + g_W e_{abc} W^b_\mu \pi_c, \qquad D_\mu a_a = \partial_\mu a_a + g_W e_{abc} W^b_\mu a_c\ ,$$

$$D_\mu K = \partial_\mu K - \frac{i}{2} g_1 B_\mu - \frac{i}{2} g_W W^a_\mu \tau_a K, \qquad D_\mu H = \partial_\mu H - \frac{i}{2} g_1 B_\mu - \frac{i}{2} g_W W^a_\mu \tau_a H$$

Structure of the theory has certain similarities to the class of THDMs!

SU(3)LxSU(3)R composite Higgs model: spectrum

Unbroken EW phase:

$$\langle 0| : \bar{D}S + \bar{S}D : |0\rangle = 0$$

diagonal T-quark and T-gluon condensates only!

$$\langle 0| : \bar{U}U : |0\rangle = \langle 0| : \bar{D}D : |0\rangle = \langle 0| : \bar{S}S : |0\rangle = -\ell_{TC}\langle 0| : \frac{\alpha_{TC}}{\pi} T^n_{\mu\nu} T^{\mu\nu}_n : |0\rangle$$

Two scalar mass scales:

$$M^2_{\sigma(0)} = 2(\lambda_1 + \lambda_2)u^2 - \Lambda_3 u + M^2_{\pi(0)}$$

$$M^2_{a(0)} = M^2_{H(0)} = M^2_{f(0)} = 2\lambda_2 u^2 + 2\Lambda_3 u + M^2_{\pi(0)}$$

+ $\delta \equiv v/u$

Only five free parameters!

Two pseudoscalar mass scales:

$$M^2_{\eta'(0)} = 3\Lambda_3 u + M^2_{\pi(0)}$$

$$M^2_{\pi(0)} = M^2_{K(0)} = M^2_{\eta(0)} = -\frac{\varkappa}{u}\langle 0| : \bar{\mathcal{Q}}\mathcal{Q} : |0\rangle$$

Broken EW phase:

$$\left.\begin{array}{c}\langle 0| : \bar{D}S + \bar{S}D : |0\rangle \neq 0 \\ m_S \simeq m_Q \ll \Lambda_{\rm TC}\end{array}\right\}$$

$$H = (H^+, \; H^0)$$

$$H = (\bar{S}Q) = \frac{1}{\sqrt{2}}\begin{pmatrix} 0 \\ v + h \end{pmatrix}$$

$$\frac{a_0 + f_0}{\sqrt{2}} + \; \ldots$$

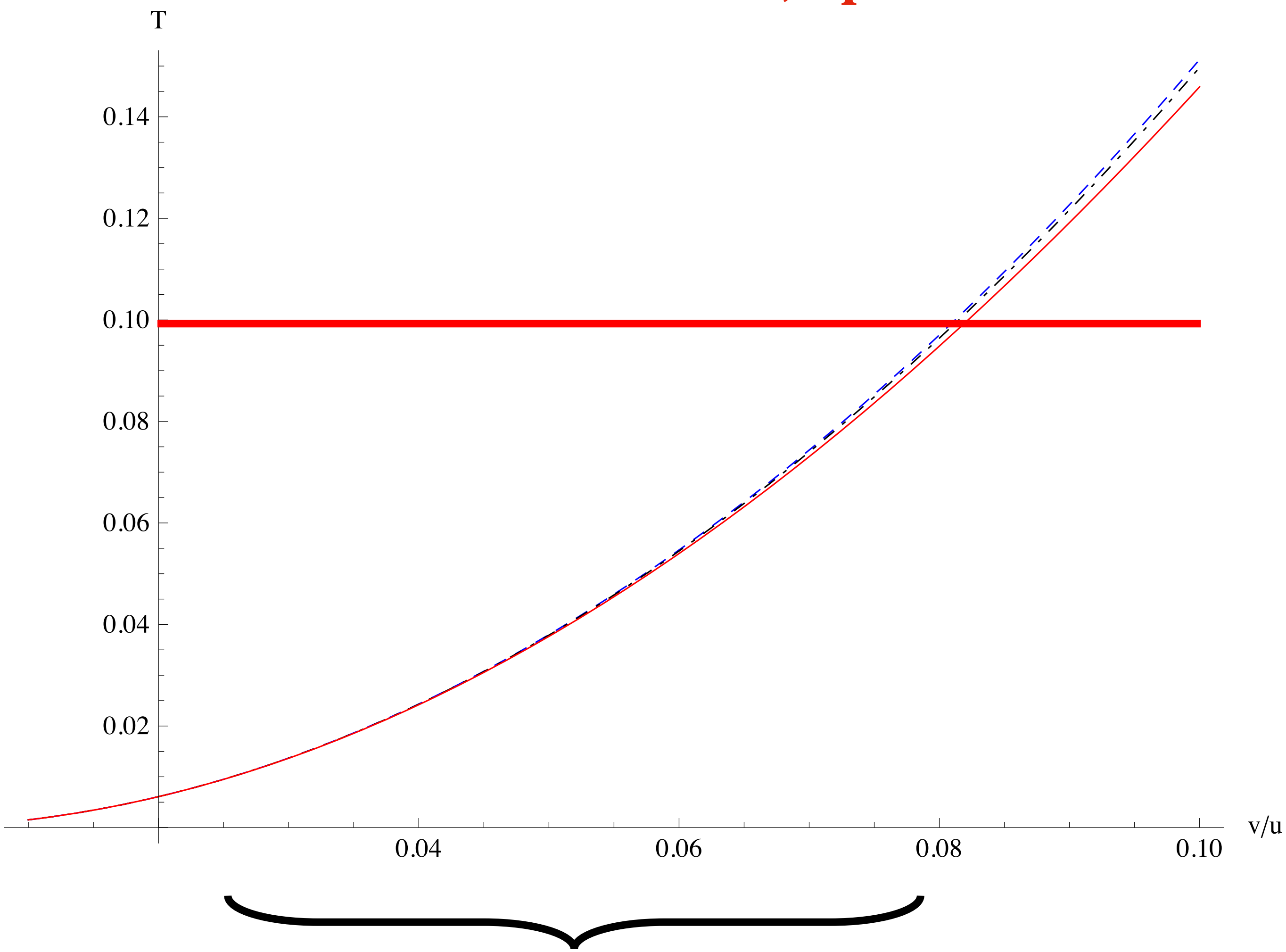
$$v \approx -\sqrt{\frac{3}{2}} \cdot \frac{\varkappa\langle 0| : \bar{D}S + \bar{S}D : |0\rangle}{M^2_{H(0)}}$$

$\delta \ll 1$ **Vacuum is stable!**

$$M^2_\sigma = M^2_{\sigma(0)} \qquad M^2_H = M^2_{H(0)} \qquad M^2_{a_0} = M^2_{H(0)} - \frac{\kappa_2}{3\sqrt{2}}\delta \qquad M^2_{f_0} = M^2_{H(0)} + \frac{\kappa_2}{3\sqrt{2}}\delta$$

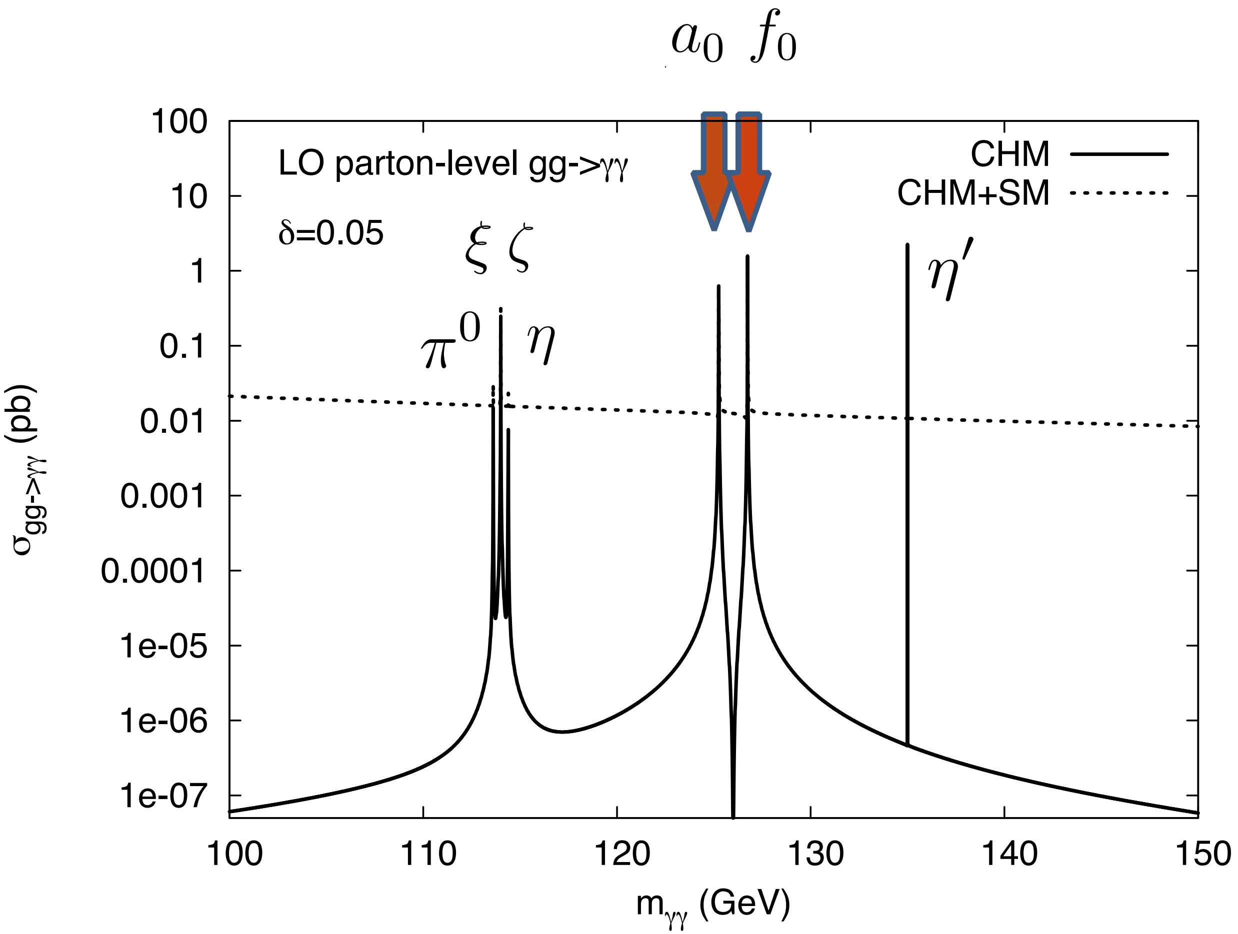
SU(3)LxSU(3)R CHM: oblique corrections

S,U parameters are vanishingly small!



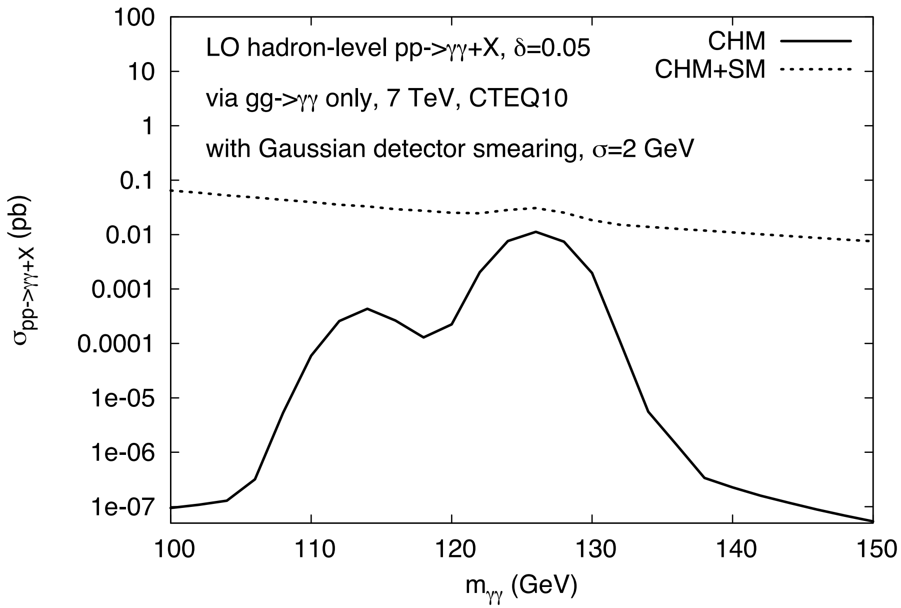
a noticeable decoupling of the T-confinement scale from the EWSB scale is favoured!

Fine structure of the Higgs signal in SU(3)LxSU(3)R

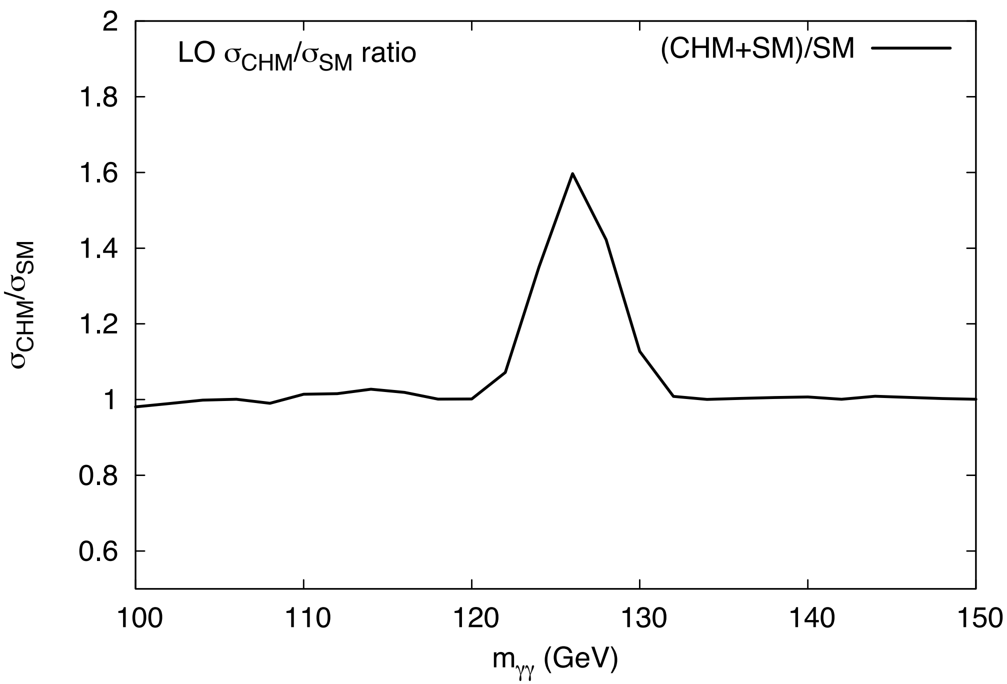


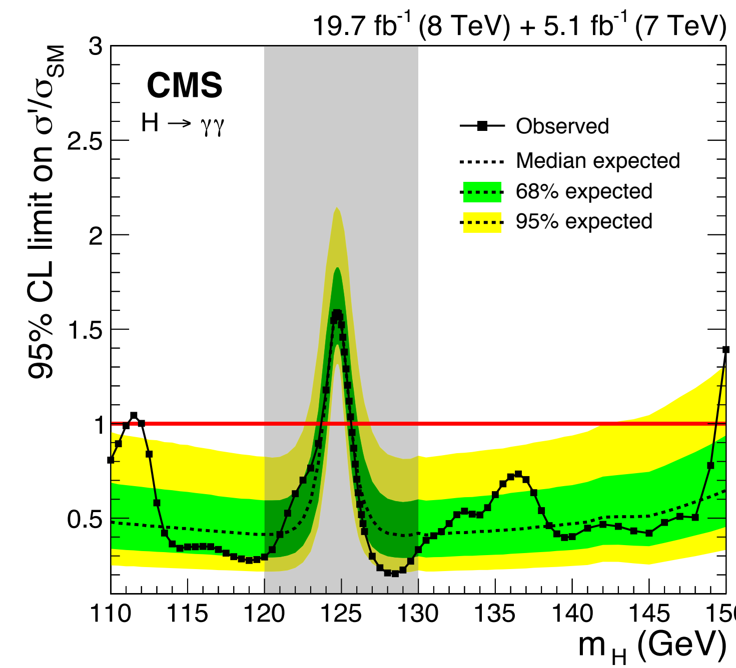
The main signature of the Higgs compositeness in this scenario – a fine structure of the Higgs signal with nearly-degenerate Higgs-like resonances!

Composite Higgs model vs observations



sensitivity to the second resonance is severely degraded!





Summary

- The **vector-like nature of weak interactions** in the T-quark sector, naturally emerging **in $SU(2)_{TC}$ theory**, along with **a SM-like Higgs mechanism**, eliminates all the known troubles of previous TC-based models

- As a possible **mechanism dynamical EWSB**, the VLTC model naturally leads to **an effective Higgs mechanism** of the SM, composite Higgs bosons, potentially predicts a **plenty of extra Higgs-like states**, and **evades EW precision constraints**

- Remarkably, the **composite Higgs model with three T-flavors** provides an extremely rich LHC phenomenology of light composites and predicts a **double-hump fine structure** of the Higgs signal, discovery of which may require a dedicated high-precision study of the low mass region at high statistics.