Vector-Like Technicolor at the LHC

Roman Pasechnik
Lund University, THEP group

At this seminar I will touch upon…

- Dissatisfaction with the Standard Model: why aren’t we happy with it?
- High-scale confinement: a possible QCD analog?
- Gauged linear σ-model and vector-like T-quark sectors
- One-doublet VLTC construction: “up-bottom” approach
- EW constraints on vector-like UV completion
- An odd vs even SU(N) confinement: DM constraints vector-like couplings
- Composite Higgs doublets and SO(2) family symmetry of the 2HDM
- Hybrid color-TC reps: a plenty of opportunities for phenomenology!
- Lightest Higgs, T-pion and T-sigma phenomenology
- Discussion and conclusions

Issues of the Standard Model

✓ **<u>Dramatically stable</u> under most stringent experimental verification**

The SM is proven to work unimaginably well up to a few TeV energy scale and passes all existing and ongoing collider tests

complete!?

all the particles predicted by the SM are discovered!

no direct exotics signals!

minimal SUSY isn't around here!?
no new particles around 100 GeV!?

no traces in EW observables!?

Higgs boson is standard!?

✓ **<u>Dramatically incomplete</u> at the same time**

Internal (conceptual) issues

I. <u>Origin and properties of the SM Higgs sector/ vacuum stability/EW symmetry breaking/ naturalness</u>

II. <u>The unique status of neutrino in the SM</u>

III. <u>Unknown origin/properties of quark/lepton generations (mass/mixing spectra)</u>

External issues

I. <u>Absence of a suitable WIMP DM candidate in the SM</u>

II. <u>Dark Energy problem… etc</u>

It is extremely difficult to imagine a SM extension consistent with all the constraints and resolves, at least, one of the issues at a time…

Dynamical EWSB

Many attractive features….

- ✓ **EWSB is triggered by a new strongly-coupled dynamics**
  (more than one confinement scale in Nature?)
- ✓ **No fundamental scalars**
  (composite Higgs?)
- ✓ **No hierarchy problem, no fine-tuning**
  (best alternative to SUSY?)
- ✓ **A plenty of new hadron-like objects, difficult to find/treat though**
  (composite Dark Matter? LHC phenomenology?)

Evolutions of DEWSB ideas/realizations….

Technicolor

Extended TC

Walking TC

Bosonic TC

Composite Higgs…

???

No reliable UV completion consistent with EW precision tests yet….

High-scale confinement: QCD-like or not?

WHY NOT??

The full power of low energy hadron physics!

a simple working hypothesis:

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

QCD

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

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

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

$$m_\pi \simeq 140\ \mathrm{MeV} \quad m_\sigma \simeq 500\ \mathrm{MeV} \quad M_Q \simeq 300\,\mathrm{MeV}$$

"techni-QCD"

$\Lambda_{\mathrm{TC}} \gtrsim v \sim 200\ \mathrm{GeV}$

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

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

$$m_{\tilde{\pi}} \gtrsim 140\,\mathrm{GeV}\,, \quad M_{\tilde{\sigma}} \gtrsim 500\,\mathrm{GeV}\,, \quad M_{\tilde{Q}} \gtrsim 300\,\mathrm{GeV}$$

Gauged linear σ-model in hadron physics

✓ *One of the most successful implementation of the gauged Nambu-Jona-Lasinio concept in hadron physics (phenomenological model)*

B.W. Lee and H.T. Nieh, Phys. Rev. **166**, 1507 (1968).
S. Gasiorowicz and D. Geffen, Rev. Mod. Phys. 41, 531 (1969);
P. Ko and S. Rudaz, Phys. Rev. D 50, 6877 (1994);
M. Urban, M. Buballa, and J. Wambach, Nucl. Phys. A697, 338 (2002).
B.D. Serot and J.D. Walecka, Acta Phys. Pol. B **21**, 655 (1992).

✓ *One of the possible effective ways to incorporate non-perturbative effects, the chiral symmetry breaking describing 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)

Local chiral group

$$\boxed{SU(2)_{\rm L} \otimes SU(2)_{\rm R} \to SU(2)_{\rm L+R}}$$

vector-like local subgroup

via interaction of sigma with <qq> condensate:

- **pseudo-Goldstone pion mass**

scalar sigma vev

- **vector-meson masses**
- **mass splitting between rho/a1**
- **constituent light quark masses**

Vector-like weak interactions of confined T-fermions

SM extended by an extra
QCD-like confined group

$$SU(N_{\rm TC})_{\rm TC} \otimes SU(3)_c \otimes SU(2)_{\rm W} \otimes U(1)_{\rm Y}$$

RP et al, arXiv:
1304.2081

acts ONLY on new
Tquark sector!

ONLY “left” SM fermions
participate in weak
interactions!

How to introduce weak
Interactions into Tquark sector?

SM-type (chiral) weak interactions
badly fail EW precision tests!

Local chiral symmetry breaking
in the confined Tquark sector
Is broken by Tsigma vev

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

What can it be used for?

Two scenarios are possible:

Scenario I: $\underline{SU(2)_{\rm V} \equiv SU(2)_{\rm W}}\,,$ ⇒ vector-like weak interactions of Tquarks!

Scenario II: $SU(2)_{\rm V} \neq SU(2)_{\rm W}\,, \quad m_{Z',W'} \gg 100\,{\rm GeV}$

No chiral anomalies!

The VLTC model: lightest Thadrons + one-doublet SM

$SU(N_{\rm TC})_{\rm TC}\otimes SU(2)_{\rm W}\otimes U(1)_{\rm Y}\qquad \tilde{Q}=\begin{pmatrix}U\\ D\end{pmatrix}$

the simplest possible Tquark sector with just one generation!

Yukawa (QCD-like) part:

$$\mathcal{L}_{\rm Y} = -g_{\rm TC}\bar{\tilde{Q}}(S+i\gamma_5\tau_a P_a)\tilde{Q}$$

$$\tilde{N},\ \tilde{Q},\ \tilde{\sigma},\ \tilde{\pi},\ \tilde{\omega},\ \tilde{\rho},\ \tilde{f},\ \tilde{a},\ \ldots$$

scalar T-sigma
(singlet rep.)

pseudoscalar T-pions
(adjoint rep.)

Lightest Tglueball

collective excitation of Tquark condensate

Kinetic terms:

$$\mathcal{L}_{kin} = \frac{1}{2}\partial_\mu S\,\partial^\mu S+\frac{1}{2}D_\mu P_a\,D^\mu P_a + i\bar{\tilde{Q}}\hat{D}\tilde{Q}$$

$$\hat{D}\tilde{Q}=\gamma^\mu\left(\partial_\mu-\frac{iY_{\tilde{Q}}}{2}g'B_\mu-\frac{i}{2}gW_\mu^a\tau_a\right)\tilde{Q},\qquad D_\mu P_a=\partial_\mu P_a+g\epsilon_{abc}W_\mu^b P_c$$

Potential part:

$$\mathcal{L}_{U,\,\rm self}=\frac{1}{2}\mu_{\rm S}^2(S^2+P^2)+\mu_{\rm H}^2\mathcal{H}^2-\frac{1}{4}\lambda_{\rm TC}(S^2+P^2)^2-\lambda_{\rm H}\mathcal{H}^4+\lambda\mathcal{H}^2(S^2+P^2)$$

mixes Higgs and new TC sectors

$$\mathcal{L}_{U,\,\rm source} = -g_{\rm TC}\,S\,\langle\bar{\tilde{Q}}\tilde{Q}\rangle\qquad P^2\equiv\textstyle\sum_a P_aP_a=\tilde{\pi}^0\tilde{\pi}^0+2\tilde{\pi}^+\tilde{\pi}^-$$

The VLTC model: EW and chiral symmetries breaking

Tsigma vev breaks the chiral symmetry, Higgs vev breaks EW symmetry

$$\mathcal{H} = \frac{1}{\sqrt{2}}\begin{pmatrix} \sqrt{2}i\phi^- \\ H + i\phi^0 \end{pmatrix}, \quad H = v + hc_\theta - \tilde{\sigma}s_\theta\,, \quad \langle\mathcal{H}\rangle = \frac{1}{\sqrt{2}}\begin{pmatrix} 0 \\ v \end{pmatrix}$$

$$v = \frac{2M_W}{g} \simeq 246\,\mathrm{GeV}\,, \quad S = u + hs_\theta + \tilde{\sigma}c_\theta\,, \quad \langle S\rangle = u \gtrsim v\,,$$

Basic assumption:

$u \sim \Lambda_{\rm TC} \sim 0.1 - 1$ TeV

Solutions of vacuum stability equations:

$$v^2 = \frac{\lambda_{\rm TC}\mu_{\rm H}^2 + \lambda(\mu_{\rm S}^2 + m_{\tilde{\pi}}^2)}{\lambda_{\rm TC}\lambda_{\rm H} - \lambda^2}$$

$$u^2 = \frac{\lambda_{\rm H}(\mu_{\rm S}^2 + m_{\tilde{\pi}}^2) + \lambda\mu_{\rm H}^2}{\lambda_{\rm TC}\lambda_{\rm H} - \lambda^2}$$

T-pion mass: $m_{\tilde{\pi}}^2 = -\frac{g_{\rm TC}\langle\bar{\tilde{Q}}\tilde{Q}\rangle}{u}$

$$\langle\bar{\tilde{Q}}\tilde{Q}\rangle < 0\,, \qquad g_{\rm TC} > 0$$

Can be as light as W!

Positively-defined scalar mass form:

$$\Delta\mathcal{L}_{sc} = -\frac{1}{2}[m_{\tilde{\pi}}^2(2\tilde{\pi}^+\tilde{\pi}^- + \tilde{\pi}^0\tilde{\pi}^0) + M_{\tilde{\sigma}}^2\tilde{\sigma}^2 + M_h^2h^2]$$

$$m_{\tilde{\pi}}^2 = \lambda_{\rm TC}u^2 - \lambda v^2 - \mu_{\rm S}^2$$

$$M_h^2 = \frac{1}{2}\left[2\lambda_{\rm TC}u^2 + m_{\tilde{\pi}}^2 + 2\lambda_{\rm H}v^2 - \sqrt{(2\lambda_{\rm TC}u^2 + m_{\tilde{\pi}}^2 - 2\lambda_{\rm H}v^2)^2 + 16\lambda^2u^2v^2}\right]$$

$$M_{\tilde{\sigma}}^2 = \frac{1}{2}\left[2\lambda_{\rm TC}u^2 + m_{\tilde{\pi}}^2 + 2\lambda_{\rm H}v^2 + \sqrt{(2\lambda_{\rm TC}u^2 + m_{\tilde{\pi}}^2 - 2\lambda_{\rm H}v^2)^2 + 16\lambda^2u^2v^2}\right]$$

h-sigma mixing angle:

$$\tan 2\theta = \frac{4\lambda uv}{2\lambda_{\rm TC}u^2 + m_{\tilde{\pi}}^2 - 2\lambda_{\rm H}v^2}$$

$$\mathrm{sign}(s_\theta) = \mathrm{sign}\left(\frac{\lambda uv}{2\lambda_{\rm H}v^2 - M_h^2}\right)$$

The VLTC model: Tquark mass spectrum

At the fundamental level, the simplest possible TC Lagrangian

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

Current Tquark mass term is allowed by symmetry!

It is not allowed for chiral SM fermions!

The coincidence $SU(2)_{\rm V} \equiv SU(2)_{\rm W}$ at the fundamental level provides arbitrary but exactly equal current Tquark masses, i.e.

$$m_U = m_D$$

This degeneracy is lifted only at the Tbaryon level by

(1) EW radiative corrections (after EWSB!),

(2) Non-perturbative UD-coupling effect (cf. di-quark in hadron physics due to exchanges of collective pion-like excitations)

Physical VLTC Lagrangian: some relevant parts…

$$\begin{aligned} L_{\bar{\tilde{Q}}\tilde{Q}V} &= \frac{1}{\sqrt{2}} g \bar{U}\gamma^\mu D \cdot W^+_\mu + \frac{1}{\sqrt{2}} g \bar{D}\gamma^\mu U \cdot W^-_\mu \\ &+ \frac{g}{c_W} Z_\mu \sum_{f=U,D} \bar{f}\gamma^\mu (t_3^f - q_f\, s_W^2) f + e \sum_{f=U,D} q_f\, \bar{f}\gamma^\mu A_\mu f \end{aligned}$$

$$\begin{aligned} & L_{\bar{\tilde{Q}}\tilde{Q}h} + L_{\bar{\tilde{Q}}\tilde{Q}\tilde{\sigma}} + L_{\bar{\tilde{Q}}\tilde{Q}\tilde{\pi}} = -g_{\rm TC}\,(c_\theta \tilde{\sigma} + s_\theta h) \cdot (\bar{U}U + \bar{D}D) \\ & -i\sqrt{2} g_{\rm TC}\, \tilde{\pi}^+ \bar{U}\gamma_5 D - i\sqrt{2} g_{\rm TC}\, \tilde{\pi}^- \bar{D}\gamma_5 U - i g_{\rm TC}\, \tilde{\pi}^0 (\bar{U}\gamma_5 U - \bar{D}\gamma_5 D) \end{aligned}$$

$$\begin{aligned} L_{\tilde{\pi}\tilde{\pi}V} &= i g W^{\mu +} \cdot (\tilde{\pi}^0 \tilde{\pi}^-_{,\mu} - \tilde{\pi}^- \tilde{\pi}^0_{,\mu}) + i g W^{\mu -} \cdot (\tilde{\pi}^+ \tilde{\pi}^0_{,\mu} - \tilde{\pi}^0 \tilde{\pi}^+_{,\mu}) \\ &+ i g (c_W Z_\mu + s_W A_\mu) \cdot (\tilde{\pi}^- \tilde{\pi}^+_{,\mu} - \tilde{\pi}^+ \tilde{\pi}^-_{,\mu}) \\ &+ g^2\, W^+_\mu W^{\mu -} \cdot (\tilde{\pi}^0 \tilde{\pi}^0 + \tilde{\pi}^+ \tilde{\pi}^-) + g^2\, (c_W Z_\mu + s_W A_\mu)^2 \cdot \tilde{\pi}^+ \tilde{\pi}^- \end{aligned}$$

$$L_{\bar{f}fh} + L_{\bar{f}f\tilde{\sigma}} = -g(c_\theta h - s_\theta \tilde{\sigma}) \cdot \frac{m_f}{2M_W} \bar{f} f$$

$$L_{h\tilde{\pi}\tilde{\pi}} = -(\lambda_{\rm TC} u\, s_\theta - \lambda v c_\theta)\, h(\tilde{\pi}^0\tilde{\pi}^0 + 2\tilde{\pi}^+\tilde{\pi}^-) = -\frac{M_h^2 - m_{\tilde{\pi}}^2}{2M_{\tilde{Q}}} g_{\rm TC} s_\theta\, h(\tilde{\pi}^0\tilde{\pi}^0 + 2\tilde{\pi}^+\tilde{\pi}^-)$$

$$L_{hWW} + L_{hZZ} = g M_W c_\theta\, h W^+_\mu W^{\mu -} + \frac{1}{2}(g^2 + g_1^2)^{1/2} M_Z c_\theta\, h Z_\mu Z^\mu \,.$$

$$L_{\tilde{\sigma}\tilde{\pi}\tilde{\pi}} = -(\lambda_{\rm TC} u c_\theta + \lambda v s_\theta)\, \tilde{\sigma}(\tilde{\pi}^0\tilde{\pi}^0 + 2\tilde{\pi}^+\tilde{\pi}^-) = -\frac{M_{\tilde{\sigma}}^2 - m_{\tilde{\pi}}^2}{2M_{\tilde{Q}}} g_{\rm TC} c_\theta\, \tilde{\sigma}(\tilde{\pi}^0\tilde{\pi}^0 + 2\tilde{\pi}^+\tilde{\pi}^-)$$

$$L_{\tilde{\sigma}WW} + L_{\tilde{\sigma}ZZ} = -g M_W s_\theta\, \tilde{\sigma} W^+_\mu W^{\mu -} - \frac{1}{2}(g^2 + g_1^2)^{1/2} M_Z s_\theta\, \tilde{\sigma} Z_\mu Z^\mu \,.$$

+ more ….

The mVLTC model: conformal limit of "techni-QCD"

What is the physical interpretation of the u and v vacua?

In the chiral limit $m_q \to 0$

the (techni)QCD Lagrangian obeys **the conformal invariance**

forbids mu-terms in the LσM Lagrangian

protects the current Tquark mass from becoming extremely large!

It is meaningful to assume naively that if

$$m_{u,d} \ll m_\pi \quad \Rightarrow \quad \mu_S \ll m_\pi$$

Tsigma vev in low-energy hadron physics has quantum-topological nature

In VLTC approach

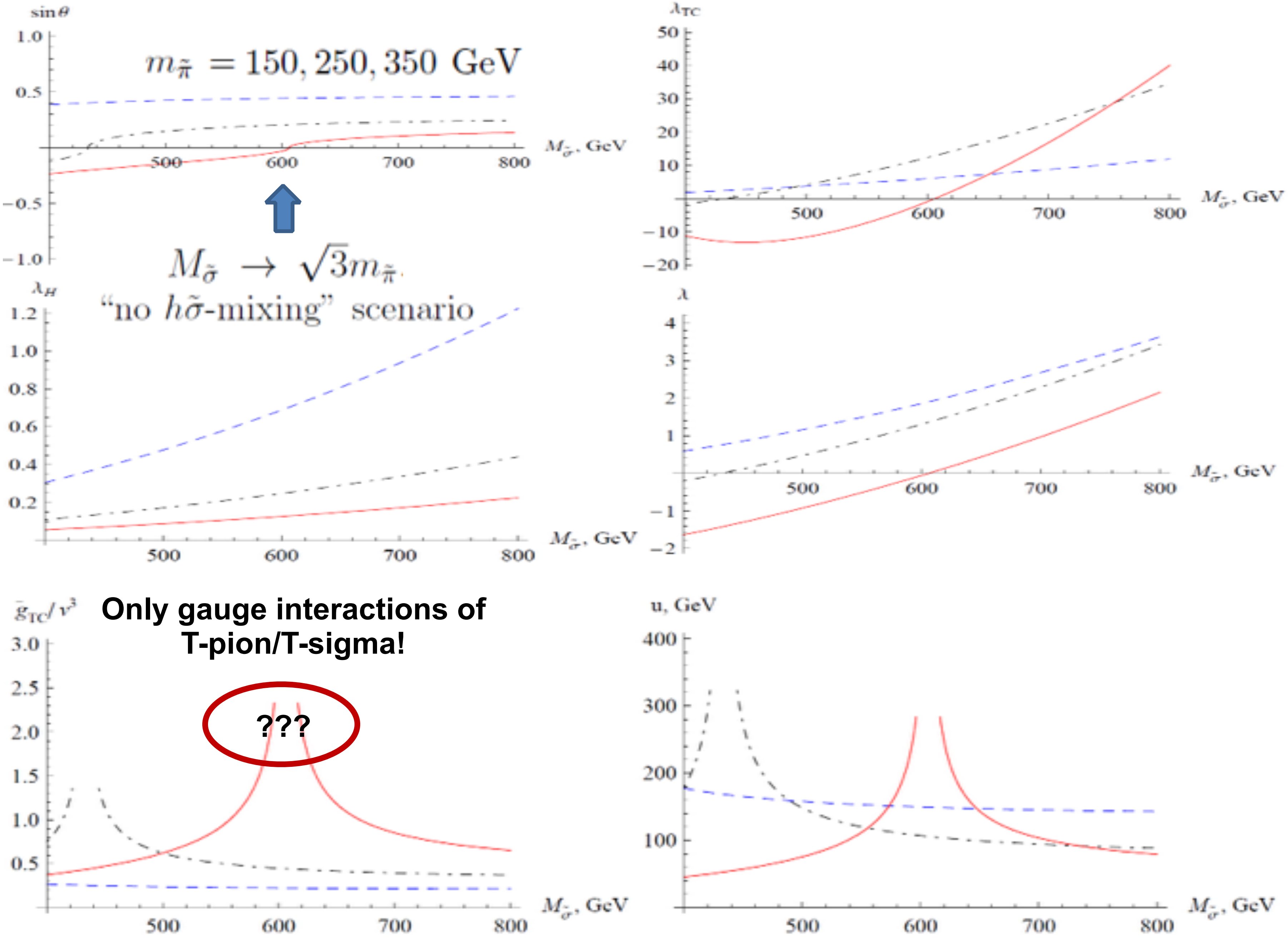
$$m_{U,D} \ll m_{\tilde{\pi}} \quad \Rightarrow \quad \mu_S \ll m_{\tilde{\pi}} \qquad \mu_{\rm H} \ll m_{\tilde{\pi}}$$

All resulting vacua are given by <QQ> condensate:

$$u = \left(\frac{\lambda_{\rm H}}{\delta}\right)^{1/3} \bar{g}_{\rm TC}^{1/3}\,, \qquad v = \left(\frac{\xi\lambda}{\lambda_{\rm H}}\right)^{1/2} \left(\frac{\lambda_{\rm H}}{\delta}\right)^{1/3} \bar{g}_{\rm TC}^{1/3} \qquad \bar{g}_{\rm TC} = g_{\rm TC}|\langle\bar{\tilde{Q}}\tilde{Q}\rangle| > 0$$

We recover the dynamical chiral/EWSB!

The mVLTC model: parameter space



$m_{\tilde{\pi}} = 150, 250, 350$ GeV

$M_{\tilde{\sigma}} \to \sqrt{3} m_{\tilde{\pi}}$

"no $h\tilde{\sigma}$-mixing" scenario

Only gauge interactions of T-pion/T-sigma!

???

Oblique corrections: definitions

$$\delta\Pi_{XY}(q^2) \equiv \Pi^{NP}_{XY}(q^2) - \Pi^{SM}_{XY}(q^2)$$

Linear order in q^2:

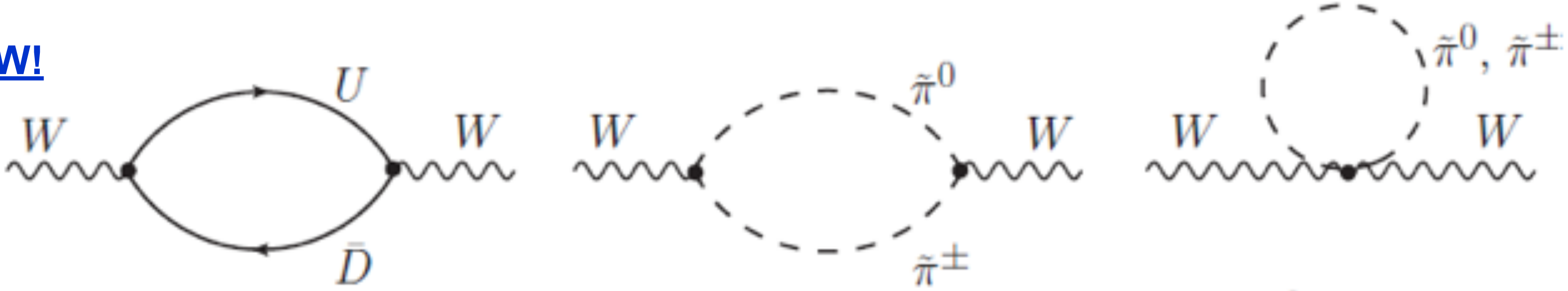
$$\begin{aligned}
\frac{\alpha}{4s_W^2c_W^2}S &= \frac{\delta\Pi_{ZZ}(M_Z^2)-\delta\Pi_{ZZ}(0)}{M_Z^2} - \frac{c_W^2-s_W^2}{c_W s_W}\delta\Pi'_{Z\gamma}(0) - \delta\Pi'_{\gamma\gamma}(0)\,,\\
\alpha T &= \frac{\delta\Pi_{WW}(0)}{M_W^2} - \frac{\delta\Pi_{ZZ}(0)}{M_Z^2}\,,\\
\frac{\alpha}{4s_W^2}U &= \frac{\delta\Pi_{WW}(M_W^2)-\delta\Pi_{WW}(0)}{M_W^2} - c_W^2\,\frac{\delta\Pi_{ZZ}(M_Z^2)-\delta\Pi_{ZZ}(0)}{M_Z^2}\\
&\quad - s_W^2\delta\Pi'_{\gamma\gamma}(0) - 2c_W s_W\delta\Pi'_{Z\gamma}(0)\,.
\end{aligned}$$

Beyond the linear order in q^2:

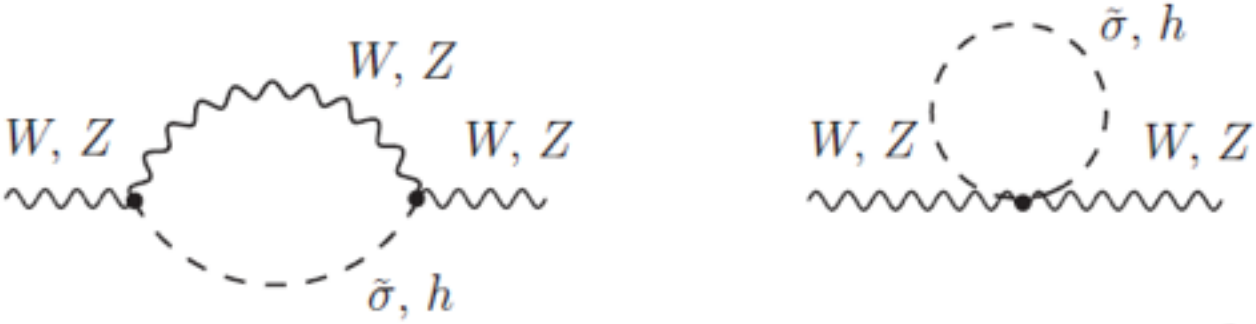
$$\begin{aligned}
\alpha V &= \delta\Pi'_{ZZ}(M_Z^2) - \frac{\delta\Pi_{ZZ}(M_Z^2)-\delta\Pi_{ZZ}(0)}{M_Z^2}\,,\\
\alpha W &= \delta\Pi'_{WW}(M_W^2) - \frac{\delta\Pi_{WW}(M_W^2)-\delta\Pi_{WW}(0)}{M_W^2}\,,\\
\alpha X &= -s_W c_W\left[\frac{\delta\Pi_{Z\gamma}(M_Z^2)}{M_Z^2} - \delta\Pi'_{Z\gamma}(0)\right].
\end{aligned}$$

Oblique corrections in the VLTC model

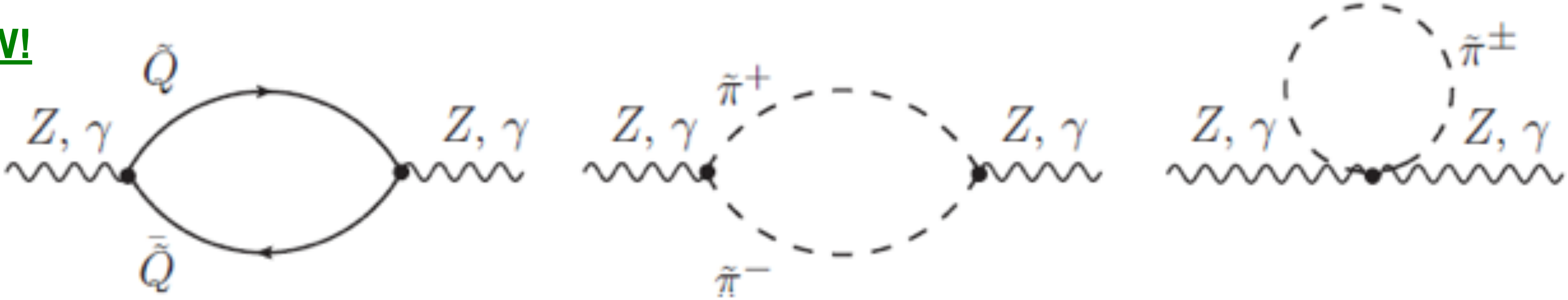
NEW!



Modified SM + Tsigma!



NEW!



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

PDG: $S = 0.00^{+0.11}_{-0.10}, \quad T = 0.02^{+0.11}_{-0.12}, \quad U = 0.08 \pm 0.11$

Oblique corrections: T-pion/T-quark contributions

Total VLTC correction

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

can be large in the T-parameter only!

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

Tpion/Tquark loops

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

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

$K,\,\kappa$	WW	ZZ	$\gamma\gamma$	$Z\gamma$
$K_{\rm XY}$	1	c^2_W	s^2_W	$c_W s_W$
$\kappa_{\rm XY},\, Y_{\tilde Q} = 0$	1	1	1	1
$\kappa_{\rm XY},\, Y_{\tilde Q} = 1/3$	1	$1 + s^4_W/9c^4_W$	$10/9$	$1 - s^2_W/9c^2_W$

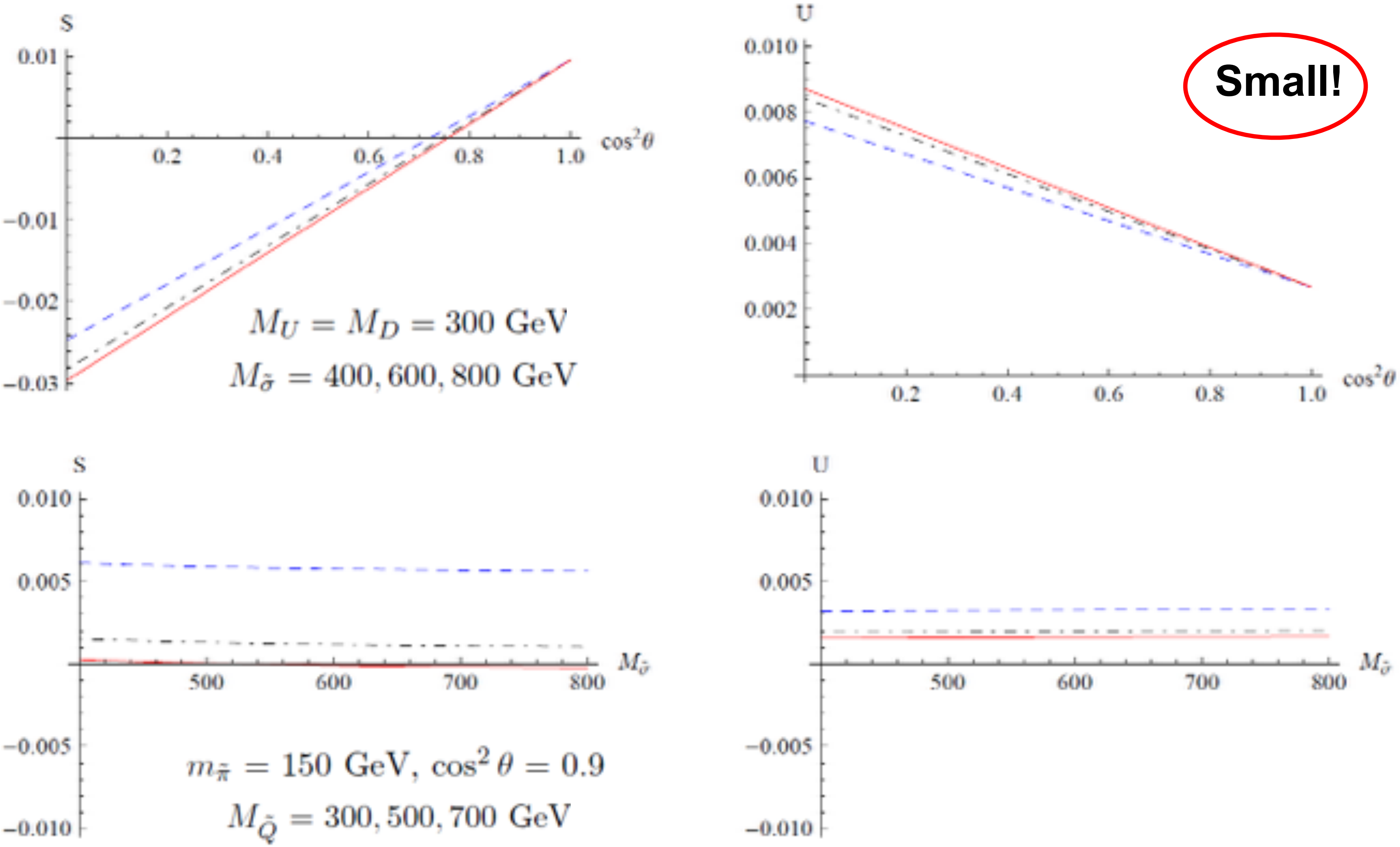
Consider for illustration

$$Y_{\tilde Q} = 0 \qquad \Rightarrow$$

$$\frac{\alpha\, S^{\tilde\pi+\tilde Q}}{4 s^2_W c^2_W} = f(M^2_Z, m^2_{\tilde\pi}, M^2_{\tilde Q}) \cdot \left[c^2_W - \frac{c^2_W - s^2_W}{c_W s_W} \cdot c_W s_W - s^2_W \right] = 0$$

$$\frac{\alpha\, U^{\tilde\pi+\tilde Q}}{4 s^2_W} = f(M^2_Z, m^2_{\tilde\pi}, M^2_{\tilde Q}) \cdot \left[1 - c^4_W - s^4_W - 2 c^2_W s^2_W \right] = 0\,,$$

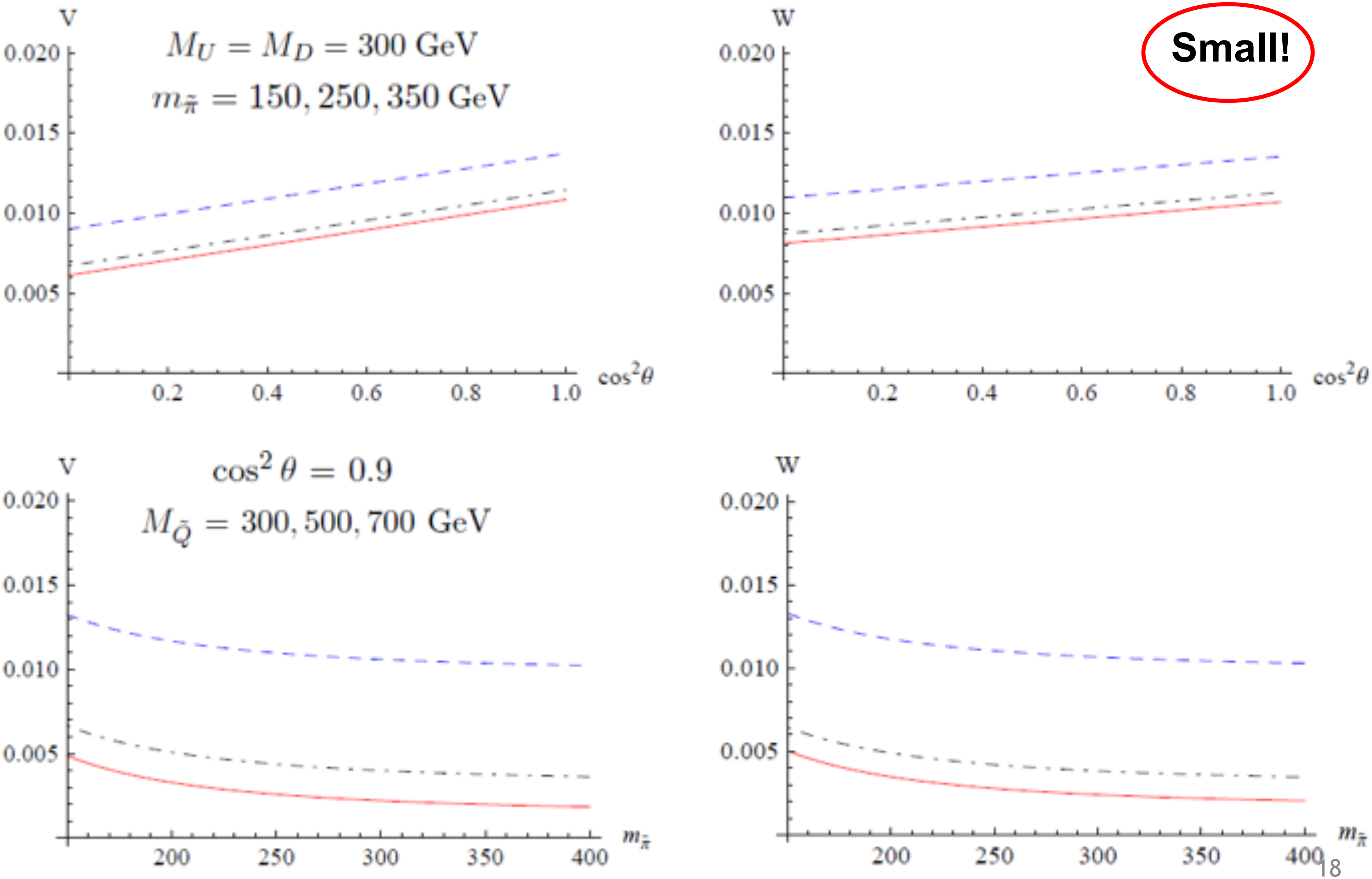
Oblique corrections: Y_Q=1/6, parameter scans



Small!

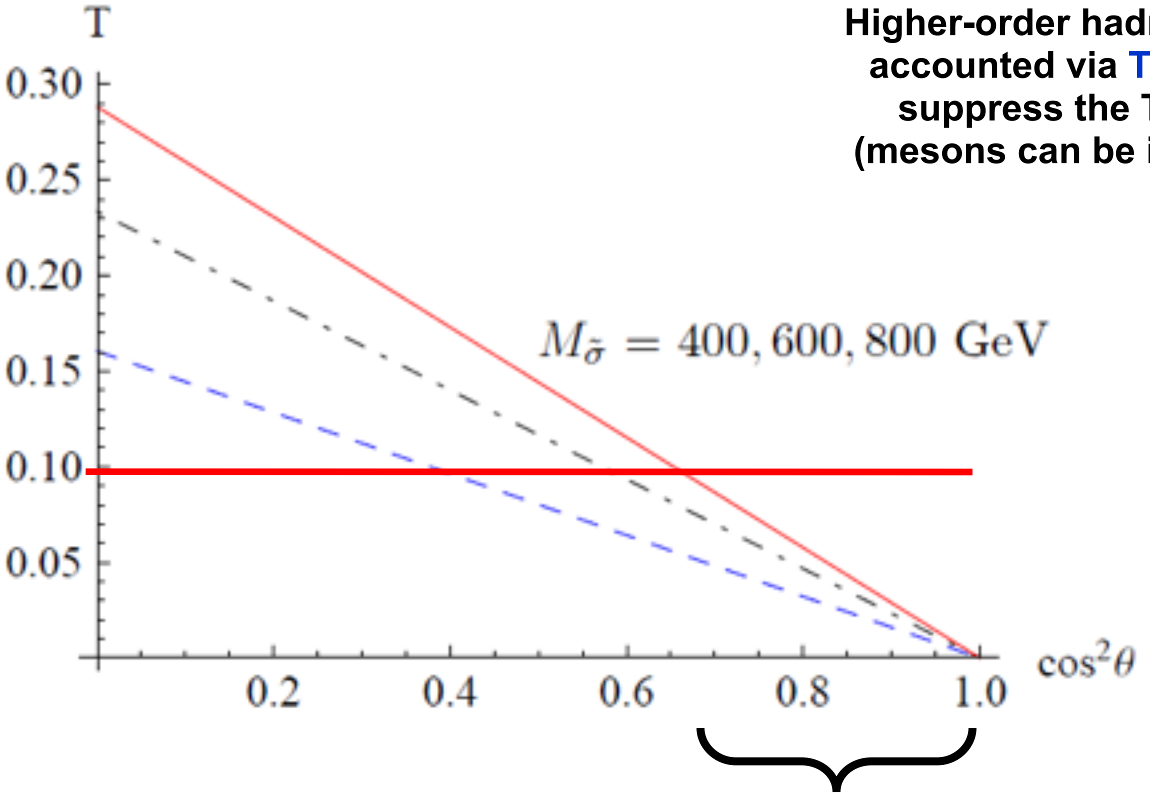
The oblique corrections are weakly dependent on Tquark hypercharge!

Oblique corrections: Y_Q=1/6, parameter scans



Small!

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



Higher-order hadron corrections accounted via T-baryon loops suppress the T-parameter! (mesons can be important too!)

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

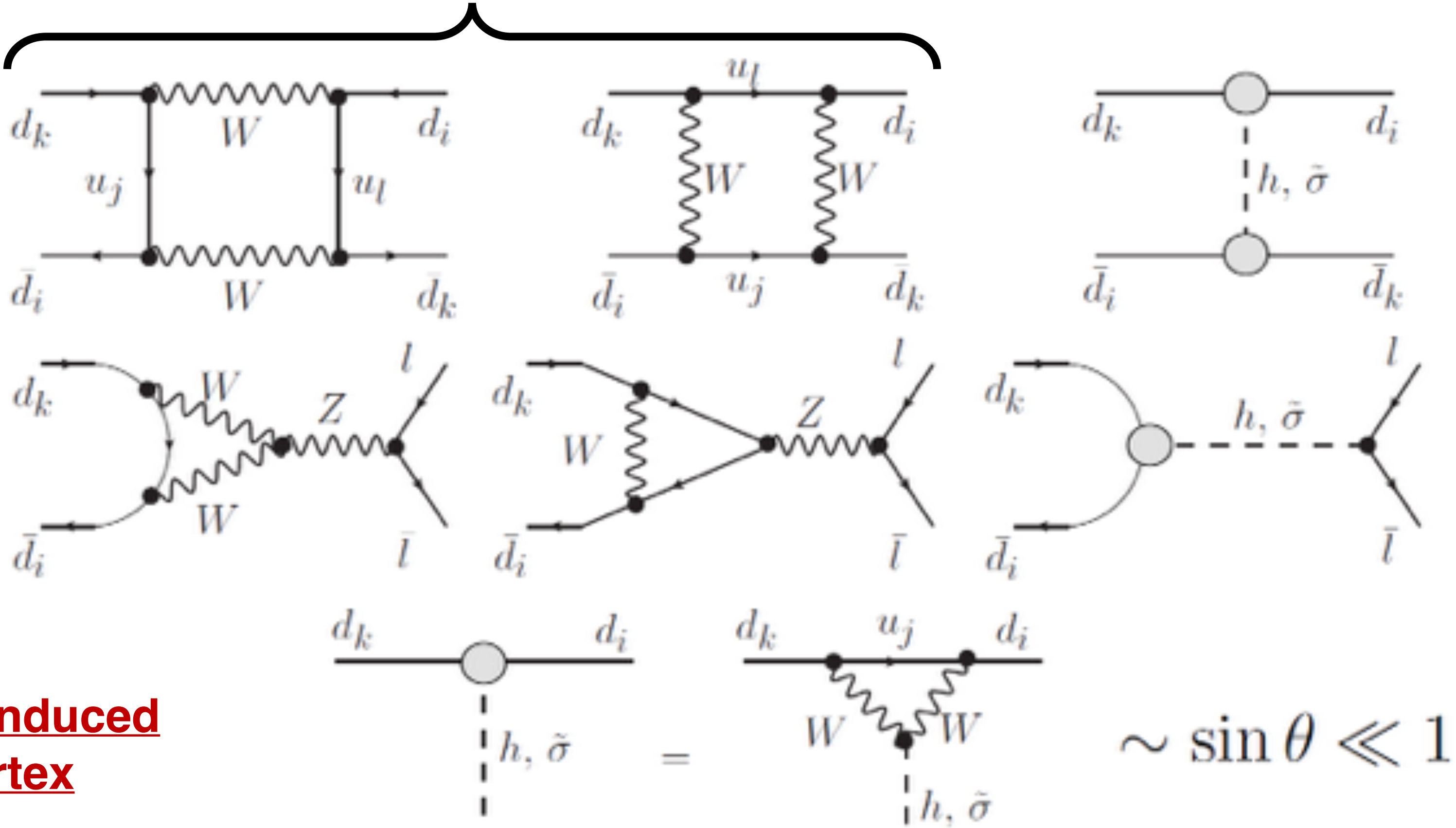
Given by scalar contribution ONLY

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

Extra FCNCs are always small!

One-loop SM part

New effect



$M^0 - \bar{M}^0$ mixing

$M \to l\bar{l}$ rare leptonic decay

Loop-induced vertex

$\sim \sin\theta \ll 1$

New TC contributions to FCNC's are strongly suppressed:

- Two-loop FCNC effects
- heavy **σ** –mass in denominators
- double suppression by a small **σ-Higgs mixing**

Small!

Fermionic T-baryons: an odd confinement group

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

I. An odd confinement group $SU(2n+1)_{\rm TC},\, n=2,3,\dots$

$$Y_Q=1/6 \quad Y_N=1/2 \quad SU(3)_{\rm TC}$$

QCD-like theory

$$\tilde N = \begin{pmatrix} P \\ N \end{pmatrix}$$

T-proton $P=(UUD)$

T-neutron $N=(DDU)$

vector-like weak interactions the same as for T-quarks!

Gauge Tbaryon interactions

$$L_{\bar{\tilde N}\tilde N Z/W} = \delta_W\frac{g_2}{\sqrt2}\,\bar P\gamma^\mu N\cdot W^+_\mu + \delta_W\frac{g_2}{\sqrt2}\,\bar N\gamma^\mu P\cdot W^-_\mu + \delta_Z\frac{g_2}{c_W}Z_\mu\sum_{f=P,N}\bar f\gamma^\mu(t_3^f-q_f\,s_W^2)f\,.$$

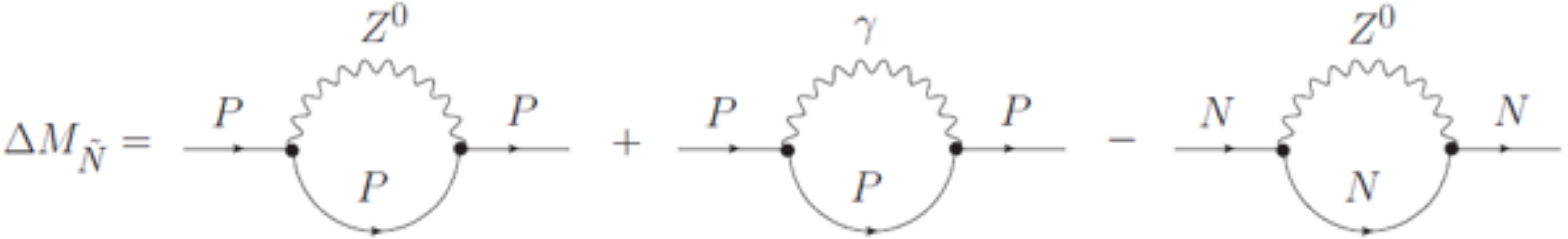
I. $\delta_{W,Z}=1\,,$ $\quad SU(2)_{\rm V}\equiv SU(2)_{\rm W}$

II. $\delta_{W,Z}\ll 1\,,$ $\quad SU(2)_{\rm V}\neq SU(2)_{\rm W}$ ⇒ **via a small Z-Z' and W-W' mixing only!**

Yukawa interactions

$$L_{\bar{\tilde N}\tilde N h}+L_{\bar{\tilde N}\tilde N\tilde\sigma}+L_{\bar{\tilde N}\tilde N\tilde\pi} = -g^N_{\rm TC}\,(c_\theta\tilde\sigma+s_\theta h)\cdot(\bar PP+\bar NN) - i\sqrt2 g^N_{\rm TC}\,\tilde\pi^+\bar P\gamma_5 N - i\sqrt2 g^N_{\rm TC}\,\tilde\pi^-\bar N\gamma_5 P - i g^N_{\rm TC}\,\tilde\pi^0(\bar P\gamma_5 P-\bar N\gamma_5 N)$$

T-baryon mass splitting: T-neutron Dark Matter?



The P-N splitting is minimal for scenario I: $M_N < M_P$

$$M_{B_T} \gg m_Z \qquad \Delta M^{\rm EW}_{B_T} = -\frac{ie^2 M_Z^2}{8\pi^4}\int \frac{(\hat q - M_{B_T})dq}{q^2(q^2-M_Z^2)[(q+p)^2-M_{B_T}^2]} \simeq \underbrace{\frac{\alpha(M_{B_T})M_Z}{2}} > 0$$

extra T-rho and/or Z' induced radiative corrections can only increase it! ← **Lower bound on P-N mass difference**

+

T-baryon number conservation hypothesis → **T-neutron Dark Matter? (e.g. ADM, SI-DM)**

The spin-independent (Z-mediated) T-neutron/nucleon scattering:

$$\sigma_{\rm SI}^{N-p} = 1.5\times 10^{-40}\,{\rm cm}^2 \times \delta_Z^2 \left(\frac{\mu}{m_p}\right)^2, \qquad \sigma_{\rm SI}^{N-n} = 2.5\times 10^{-38}\,{\rm cm}^2 \times \delta_Z^2 \left(\frac{\mu}{m_n}\right)^2$$

XENON100 bound: $-\log_{10}\left(\frac{\sigma_{\rm SI}^{\rm nucleon}}{{\rm cm}^2}\right) \simeq 44.6 - 43.4$ → $\boxed{\delta_Z \lesssim 2\times 10^{-3}}$

Vector-like Tquarks with an odd TC group are excluded!?

RP et al, arXiv: 1308.6625

Scalar T-baryons: an even confinement group

II. An even confinement group $SU(2n)_{\rm TC}$ $SU(2)_{\rm TC}$

In fact, the simplest option!

$$Y_Q = 0 \quad Y_N = 0$$

Real adjoint (spin-0) reps of $SU(2)_{\rm W}$

$$\left.\begin{array}{ll} G_a = \{UU,\ DD,\ UD\}\,, & B_{\rm T} = +1 \\ F_a = \{\bar U\bar U,\ \bar D\bar D,\ \bar U\bar D\}\,, & B_{\rm T} = -1 \end{array}\right\}$$

Complex adjoint (spin-0) reps

$$B_a = \frac{1}{\sqrt{2}}(G_a + iF_a)$$

$$B_a^* \equiv \bar B_a = \frac{1}{\sqrt{2}}(G_a - iF_a) \neq B_a$$

Physical T-baryons

$$B^\pm = \frac{1}{\sqrt{2}}(B_1 \mp iB_2)\,, \qquad B^0 \equiv B_3$$

attractive DM candidate!

Gauge T-baryon interactions

$$\mathcal{L}_{\rm TB}^{kin} = D_\mu B_a D^\mu \bar B_a$$

$$D_\mu B_a = \partial_\mu B_a + g\epsilon_{abc} W_\mu^b B^c$$

Under T-baryon number conservation hypothesis, the scalar potential is trivially extended

$$\Delta\mathcal{L}_U = \frac{1}{2}\mu_B^2 \bar B B + g_{\rm BS}(S^2 + P^2)(\bar B B) + g_{\rm BH}(H^\dagger H)(\bar B B) + g_{\rm BP}(\bar B P)(B P) + g_{4\rm B}(\bar B B)(\bar B B)$$

previous mass formulae do not change!

- ✓ a non-perturbative effect of UD-coupling ala (ud) di-quark in QCD (lightest B0)
- ✓ no vector B0-B0-Z coupling
- ✓ T-baryon terms improve T-parameter

Vector-like weak (scenario I) interactions in the SU(2)TC are allowed by DM/EW constraints!

Composite Higgs doublets from VLTC

VLTC

…plus extra SU(2)-singlet Tquarks with opposite hypercharge

$$\tilde{Q}^a = \begin{pmatrix} U^a \\ D^a \end{pmatrix}_{L+R\equiv W} \qquad Y_Q = 0$$

$$U^a_s\,, \quad Y_{U_s} = +1/2\,, \quad t^3_{U_s} = 0$$

$$D^a_s\,, \quad Y_{D_s} = -1/2\,, \quad t^3_{D_s} = 0$$

Among bound states, one finds two composite Higgs doublets -

Effective 2HDM

$$H_1 = \begin{pmatrix} U\bar{U}_s \\ D\bar{U}_s \end{pmatrix}_{L+R\equiv W} \qquad H_2 = \begin{pmatrix} U\bar{D}_s \\ D\bar{D}_s \end{pmatrix}_{L+R\equiv W} \qquad B^T_H = 0$$

$$Y_{H_1} = +1/2 \qquad Y_{H_2} = -1/2$$

EW-singlet scalars

$$\{\Phi_1, \Phi_2\} = \{U_s\bar{U}_s\,, D_s\bar{D}_s\} \qquad B^T_\Phi = 0$$

SU(2)-singlet charged scalars

$$\Psi^\pm = \{U_s\bar{D}_s\,, D_s\bar{U}_s\} \qquad B^T_\Psi = 0$$

…and a plenty of extra scalar Tbaryons $B^T \neq 0$

A probe for compositeness –
two Higgs bosons production in VBF!?

under development…

How to ensure the existence of only one lightest SM-like Higgs boson???

Global family symmetry of the SM: SO(2)

…one of the possibilities to address **on the same footing:**

- one lightest Higgs **boson only?** too wide **Higgs boson?**
- **the** quark-lepton generations problem **(new symmetry?)**
- **the** quark mixing problem
- very small neutrino **masses**

Extension of SM by flavor $SO_f(2)$ symmetry

See a discussion e.g. by Kim'86, Fukugita'89, Danko'01, Chang'02, Burdyuzha'08, Vereshkov'11

"familon" symmetry is spontaneously broken

$$q = \begin{pmatrix} u & c & t \\ d & s & b \end{pmatrix} \approx \begin{pmatrix} 0 & 1{,}2 & 174 \\ 0 & 0{,}118 & 4{,}3 \end{pmatrix} \ \mathrm{GeV}$$

$$\ell = \begin{pmatrix} \nu_e & \nu_\mu & \nu_\tau \\ e & \mu & \tau \end{pmatrix} \approx \begin{pmatrix} 0 & 0 & 0 \\ 0 & 0{,}106 & 1{,}78 \end{pmatrix} \ \mathrm{GeV}$$

$$\begin{pmatrix} V_{ud} & V_{us} & V_{ub} \\ V_{cd} & V_{cs} & V_{cb} \\ V_{td} & V_{ts} & V_{tb} \end{pmatrix} \approx \begin{pmatrix} \cos\theta & \sin\theta & 0 \\ -\sin\theta & \cos\theta & 0 \\ 0 & 0 & 1 \end{pmatrix}$$

Quark/lepton SO(2) representations:

Vector: $q_{L_A},\quad u_{R_A},\quad d_{R_A},\qquad \ell_{L_A},\quad e_{R_A},\quad \nu_{R_A},$

Scalar: $q_{L_3},\quad u_{R_3},\quad d_{R_3},\qquad \ell_{L_3},\quad e_{R_3},\quad \nu_{R_3},$

$A = 1,\, 2$

Two-doublet Higgs sector:

New real scalar field (EW singlet, SO(2) vector):

Fundamental (EW)
AND **vector SO(2)**

$$\begin{aligned} H_1' &= e^{\frac{i}{2}g_1\theta + \frac{i}{2}g_2\theta_a\tau_a}(\ \ H_1\cos\omega + H_2\sin\omega), \\ H_2' &= e^{\frac{i}{2}g_1\theta + \frac{i}{2}g_2\theta_a\tau_a}(-H_1\sin\omega + H_2\cos\omega), \\ \mathrm{CP}\, H_A &= \ \ H_A^{+}. \end{aligned}$$

$$\begin{aligned} \Phi_1' &= \ \ \Phi_1\cos\omega + \Phi_2\sin\omega, \\ \Phi_2' &= -\Phi_1\sin\omega + \Phi_2\cos\omega, \\ \mathrm{CP}\, \Phi_A &= \ \ \Phi_A. \end{aligned}$$

Spontaneous family symmetry breaking

usual EW scale:

$$\langle v_{vac}\rangle \sim 245\ \mathrm{GeV}$$

one lightest scalar
(composite?) Higgs boson

h^0

massless Goldstone
weakly interacting (composite?) familon

f

new "familon" scale:

$$u \gg v$$

$$H^{\pm}, H,\ A,\ \Phi_{1,2}$$

..are far away from experimentally
accessible energy scales!

Experimental constraints on familon decays of fermions:

$$\Gamma\left(\tau^- \to e^- f\right)/\Gamma\left(\tau^- \to e^-\nu\bar{\nu}\right) < 1{,}5\times 10^{-2}$$

$$\Gamma\left(\mu \to e f\right)/\Gamma\left(\mu \to e\nu\bar{\nu}\right) < 3\times 10^{-4}$$

$$\boxed{u \gtrsim 10^{8} - 10^{9}\ \mathrm{GeV}}$$

Non-perturbative interactions with the TQuark-TGluon condensate excitations (T-pions/T-sigma) may give a large mass to the familon

**NOTE: massless "familon mode"
dominates the Higgs decay
(provides a constraint on mf!)**

$$\frac{\Gamma(h^0\to\bar{b}b)}{\Gamma(h^0\to ff)} = \frac{1}{2}\left(\frac{m_b m_{h^0}}{2\xi v^2}\right)^2 \approx \left(\frac{m_{h^0}}{1{,}5\ \text{ТэВ}}\right)^2 \approx 10^{-2}$$

Possibly light familon Dark Matter component?

under development…

Hybrid color-TC representations and VLTC

SM $$SU(3)_c \otimes SU(2)_W \otimes U(1)_Y \quad q^i = \begin{pmatrix} u^i \\ d^i \end{pmatrix}_L \left.\right\} \quad \begin{matrix} Y_q = 1/6,\ B^T_{u,d} = 0, \\ B_{u,d} = +1/3,\ t^3_{u,d} = \pm 1/2 \end{matrix}$$

VLTC $$SU(2)_{TC} \otimes SU(2)_W \otimes U(1)_Y \quad \tilde{Q}^a = \begin{pmatrix} U^a \\ D^a \end{pmatrix}_{L+R\equiv W} \left.\right\} \quad \begin{matrix} Y_Q = 0,\ B^T_{U,D} = +1/2, \\ B_{U,D} = 0,\ t^3_{U,D} = \pm 1/2 \end{matrix}$$

Hybrid C-TC $$SU(3)_c \otimes SU(2)_{TC} \otimes U(1)_Y \quad C^{ai} \left.\right\} \quad \begin{matrix} Y_C = 1/6,\ B^T_C = +1/2, \\ B_C = +1/3,\ t^3_C = 0 \end{matrix}$$

A plenty of extra heavy exotic states appear immediately!

Scalar quarks	Scalar gluons	"Superbaryons"	"Superleptons"
$C^{ai}\bar{Q}_a$			$C^{ai}\bar{Q}_a\bar{u}_i$
$\epsilon^{ab}C^{ak}Q^b$	$C^{bi}(\lambda^j_i)^r\gamma^\mu\bar{C}_{bj}$	$\epsilon^{ikl}\epsilon^{ab}C^{ak}C^{bl}q^i$	$C^{ai}\bar{Q}_a\bar{d}_i$
$\epsilon^{ikl}\epsilon^{ab}C^{ak}C^{bl}$			

Rich New Physics phenomenology!

under development…

Important example: partial neutrino compositeness

Can we get small neutrino masses in the VLTC?

One of the states predicted
by VLTC + hybrid C-TC

$$\nu_{\mathrm{TC}} \equiv C^{ia}(\bar{U}_a \bar{d}_i + \bar{D}_a \bar{u}_i)$$

$$J = 1/2\,,\; B = 0\,,\; B^T = 0\,,\; q = 0\,,\; t^3 = 0$$

…can be very heavy $M_{\nu_{\mathrm{TC}}} \gg 100\,\mathrm{GeV}\,, \quad m_C \gg m_Q$

Both chiral components $(\nu_{\mathrm{TC}})_{\mathrm{R}}\,,\ (\nu_{\mathrm{TC}})^c_{\mathrm{L}}$ have the same quantum numbers as right-handed neutrinos!

Standard “see-saw” mechanism at work!

Physical neutrino states after EWSB

$$\nu_{\mathrm{R}}^{\mathrm{heavy}} = -b\nu + a(\nu_{\mathrm{TC}})^c_{\mathrm{L}} \qquad M_{\nu_{\mathrm{R}}^{\mathrm{heavy}}} \sim M$$

$$m \sim 1\,\mathrm{MeV}\,,\; M \sim 1\,\mathrm{TeV}$$

$$\nu_{\mathrm{L}}^{\mathrm{light}} = a\nu + b(\nu_{\mathrm{TC}})_{\mathrm{R}} \qquad m_{\nu_{\mathrm{L}}^{\mathrm{light}}} \sim \frac{m^2}{M}$$

$$a = \frac{M}{(M^2+m^2)^{1/2}}\,,\; b = \frac{m}{(M^2+m^2)^{1/2}}$$

partially composite neutrino!

BUT! Fraction is very small $b \sim 10^{-6}$

Neutrino participate in
decays of all composites
containing C-Tquark!

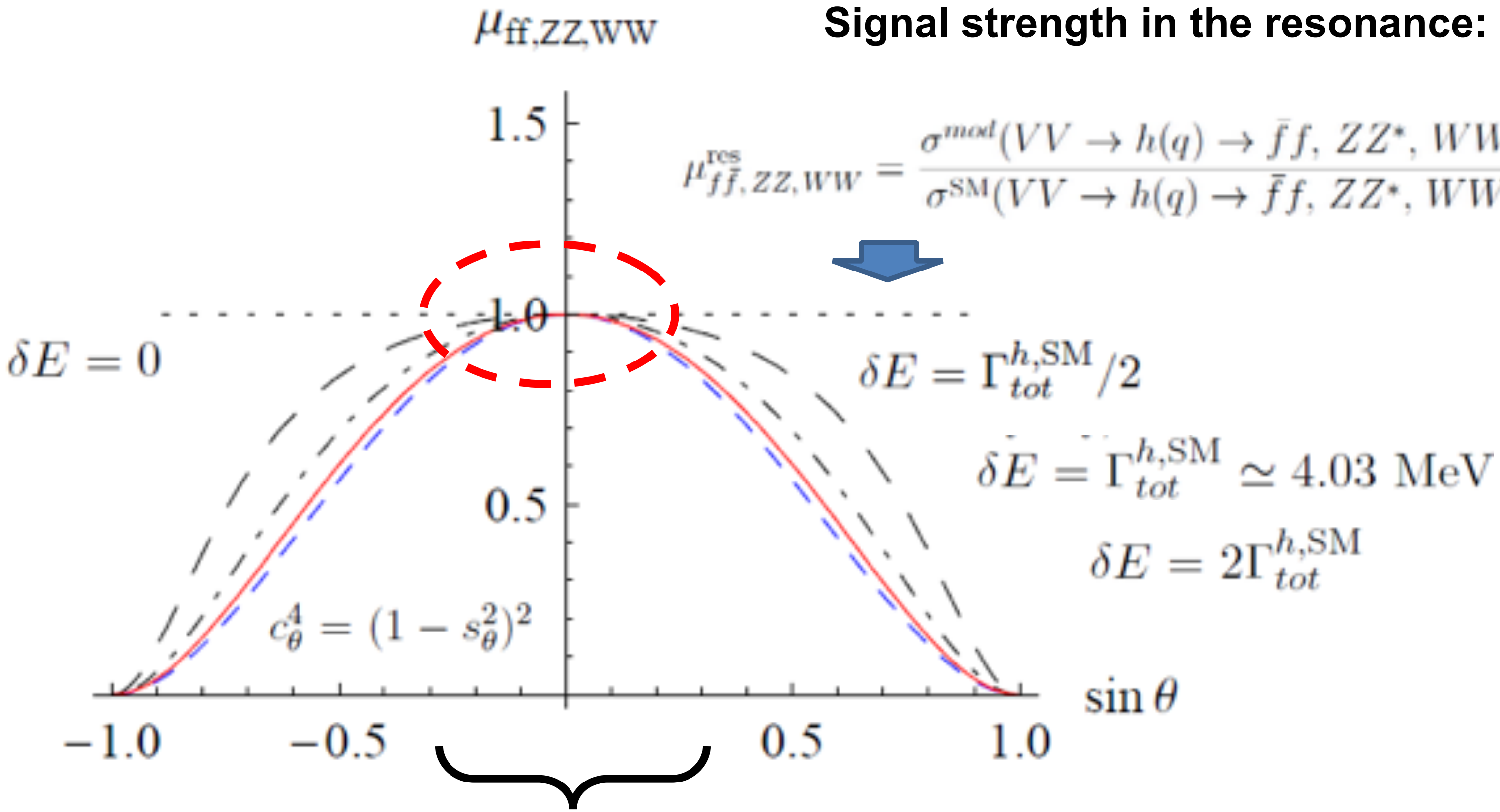
Observable effect –
long-lived (metastable)
heavy composites!

under development…

Higgs signal strength in the VLTC: Born channels

Can be sensitive to a Higgs resonance smearing!

$$\mu_{\rm XY}(\delta E) = \frac{\int_{M_h-\delta E}^{M_h+\delta E} \sigma^{mod}_{\rm XY}(q)dq}{\int_{M_h-\delta E}^{M_h+\delta E} \sigma^{\rm SM}_{\rm XY}(q)dq}$$



Signal strength in the resonance:

$$\mu^{\rm res}_{f\bar f,ZZ,WW} = \frac{\sigma^{mod}(VV \to h(q) \to \bar f f,\, ZZ^*,\, WW^*)}{\sigma^{\rm SM}(VV \to h(q) \to \bar f f,\, ZZ^*,\, WW^*)} \simeq 1$$

Weakly deviates from unity for a small mixing

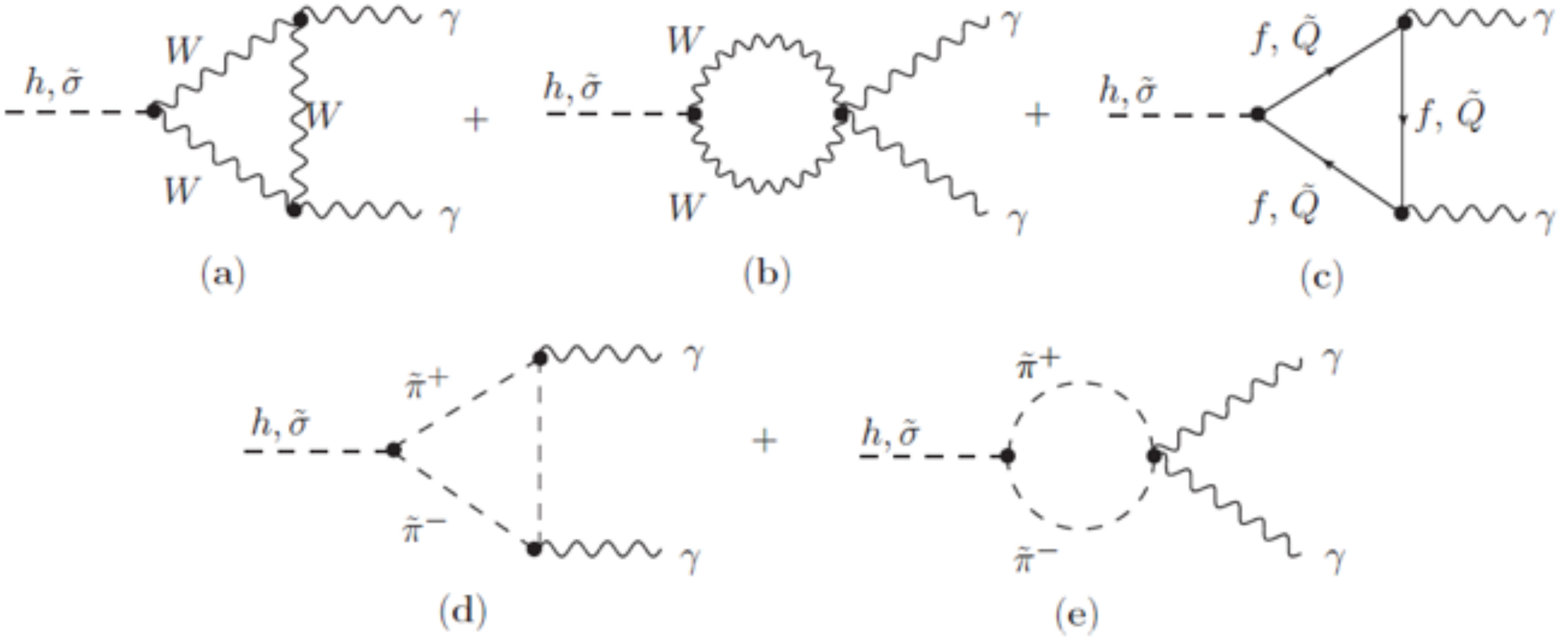
Higgs signal strength: loop-induced γγ

Signal strength in the resonance:

$$\mu_{\gamma\gamma}^{\rm res} = \frac{\sigma^{mod}(h\to\gamma\gamma)}{\sigma^{\rm SM}(h\to\gamma\gamma)} \simeq \frac{1}{c_\theta^2}\frac{\Gamma^{mod}(h\to\gamma\gamma)}{\Gamma^{\rm SM}(h\to\gamma\gamma)} \simeq \frac{1}{c_\theta^2}\frac{|A_W + A_f + A_{\tilde\pi} + A_{\tilde Q}|^2}{|A_W^{\rm SM} + A_f^{\rm SM}|^2}$$

Heavy composites in loops are not included!

VLTC contributions + modified SM terms:



The sums of gauge/fermion loops and Tpion loops are separately finite!

Higgs→γγ decay width in the VLTC

$$\Gamma^{mod}(h \to \gamma\gamma) = \frac{\alpha^2 M_h}{16\pi^3} \cdot |F_W + F_{top} + F_{\tilde{\pi}} + F_{\tilde{Q}}|^2$$

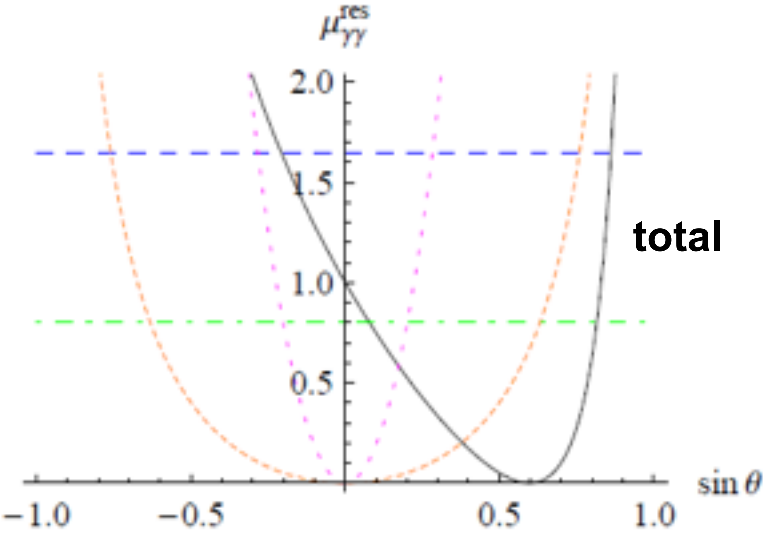
where individual contributions:

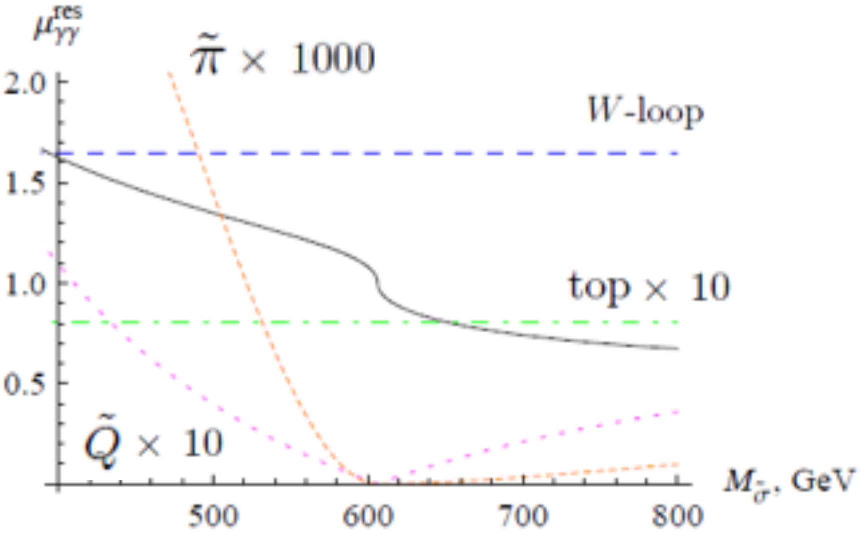
$$F_W = \frac{1}{8}\, g\, c_\theta\, \frac{M_h}{M_W} \cdot \Big[2 + 3\beta_W + 3\beta_W(2-\beta_W) f(\beta_W)\Big]\,, \qquad f(\beta) = \arcsin^2 \frac{1}{\sqrt{\beta}} \qquad \beta_X = \frac{4m_X^2}{M_h^2}$$

$$F_{top} = -\frac{4}{3}\, g\, c_\theta\, \frac{m_{top}^2}{M_h M_W} \Big[1 + (1-\beta_{top}) f(\beta_{top})\Big]\,,$$

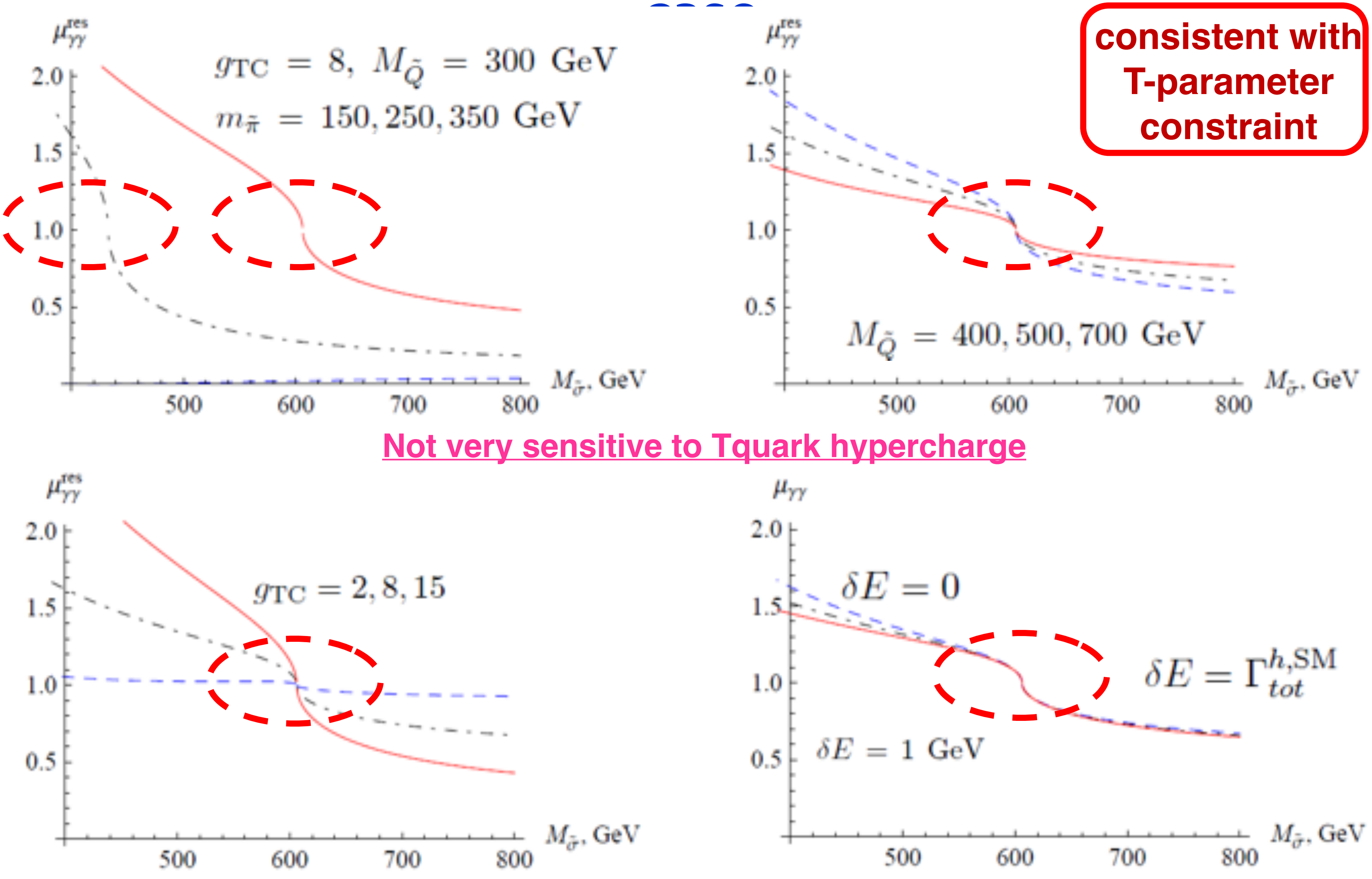
$$\left.\begin{aligned} F_{\tilde{\pi}} &= -\frac{g_{h\tilde{\pi}}}{2M_h} \Big[1 - \beta_{\tilde{\pi}} f(\beta_{\tilde{\pi}})\Big], \qquad g_{h\tilde{\pi}} = -2(\lambda_{\rm TC}\, u s_\theta - \lambda\, v c_\theta)\,, \\ F_{\tilde{Q}} &= -2N_{\rm TC}(q_U^2 + q_D^2)\, g_{\rm TC}\, s_\theta\, \frac{M_{\tilde{Q}}}{M_h} \Big[1 + (1-\beta_{\tilde{Q}}) f(\beta_{\tilde{Q}})\Big]\,, \end{aligned}\right\}$$

Disappear in the small mixing!





Higgs γγ-signal strength in the mVLTC: the Y_Q=1/6



consistent with T-parameter constraint

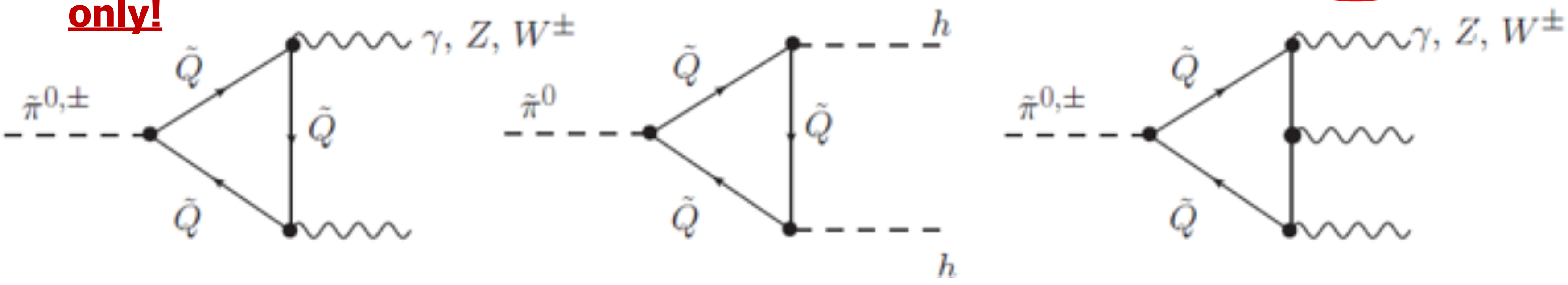
Not very sensitive to Tquark hypercharge

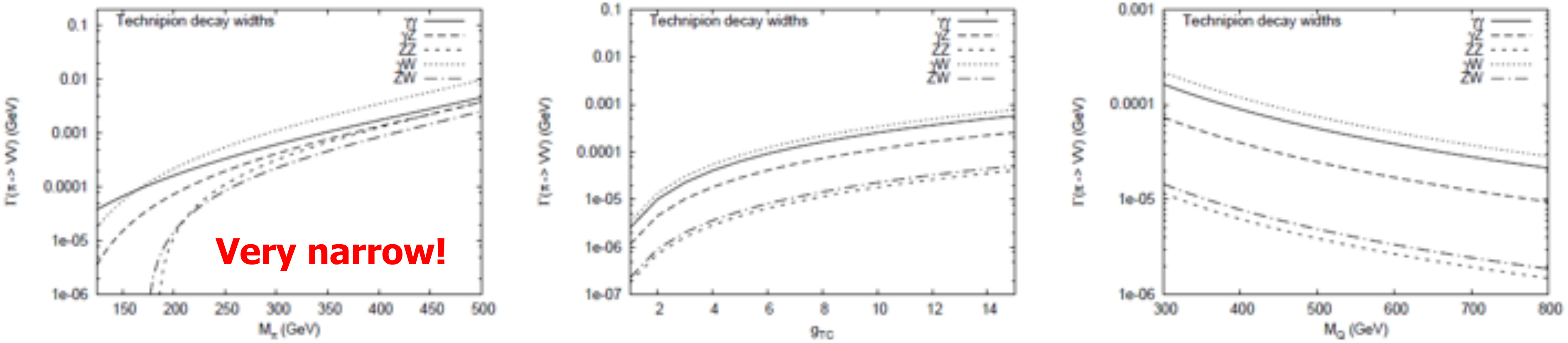
The deviations in the Higgs couplings can be regulated in a desired way

T-pion decay: the Y_Q=1/6 case

$Y_Q = 0$

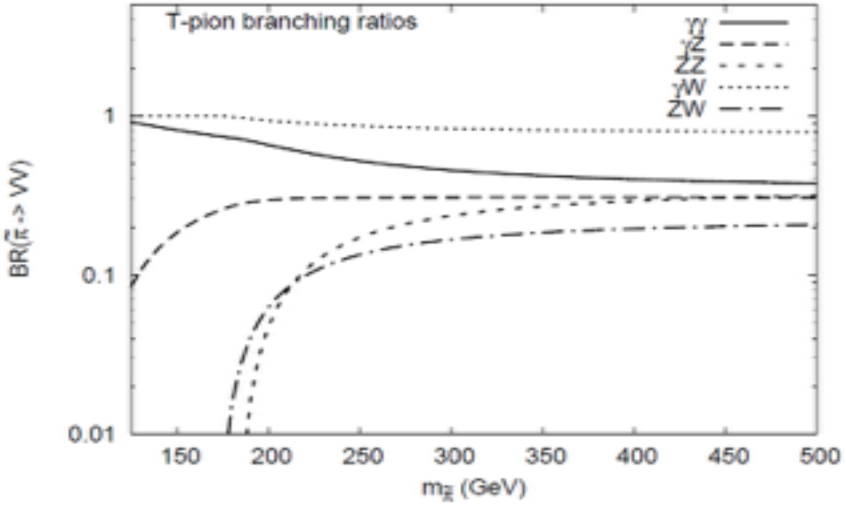
Loop-induced only!





Very narrow!

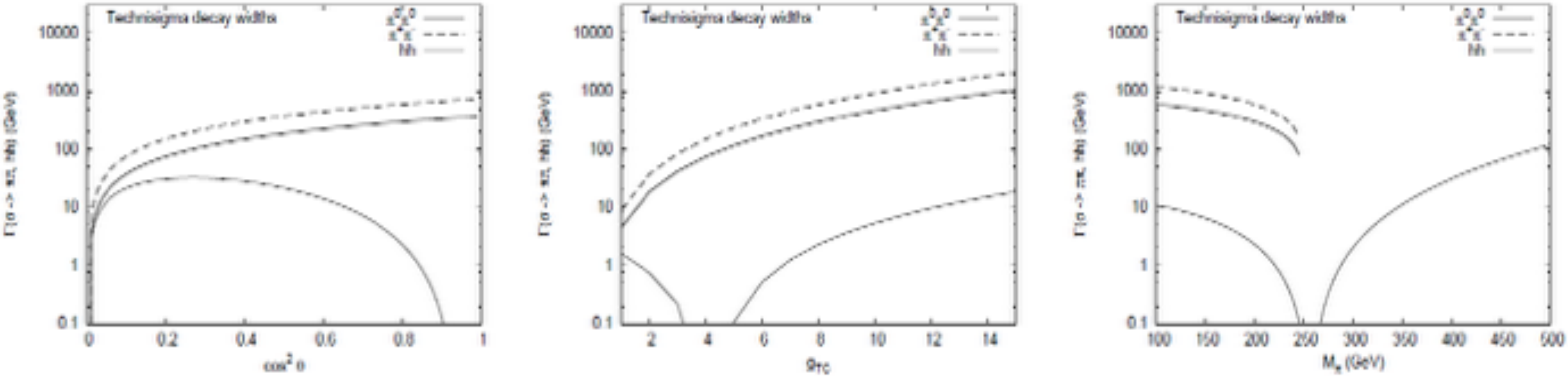
WW channel is forbidden by symmetry



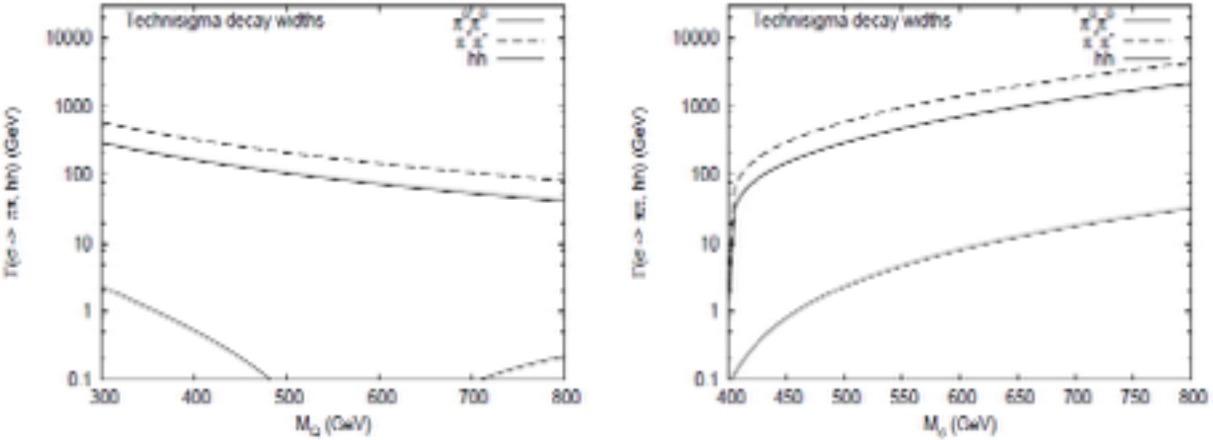
$\tilde{\pi}^0 \to \gamma\gamma \quad \tilde{\pi}^\pm \to \gamma W^\pm$

Dominate for light Tpions!

T-sigma decay widths



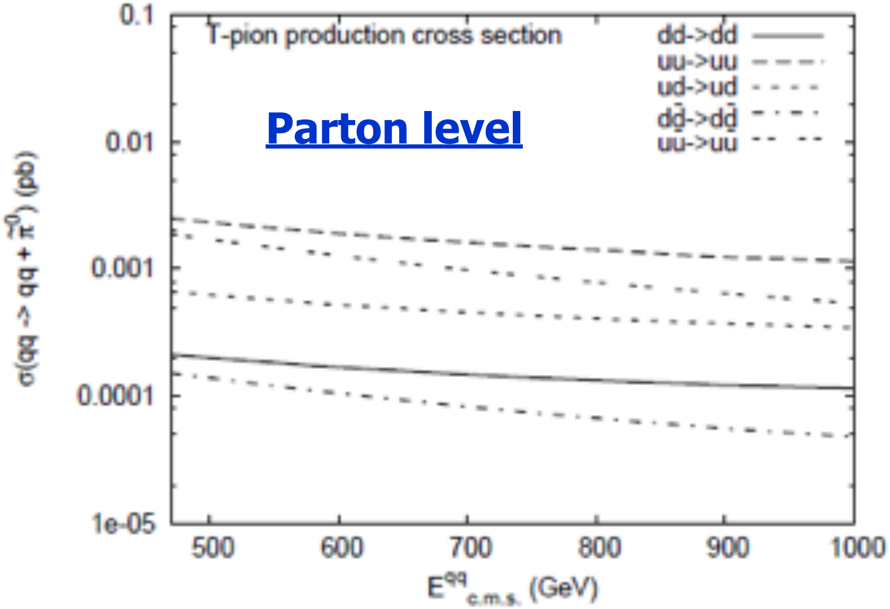
Mostly to T-pions!



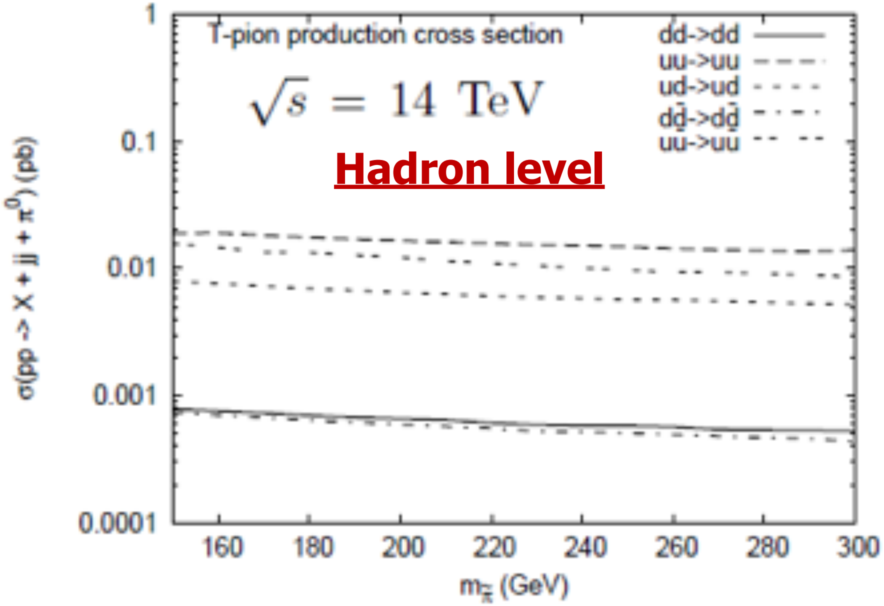
$$m_{\tilde\pi} = 200 \text{ GeV},\ M_{\tilde Q} = 300 \text{ GeV},\ M_{\tilde\sigma} = 500 \text{ GeV},\ c_\theta^2 = 0.8 \quad g_{\mathrm{TC}} = 8$$

T-sigma width is of the order of its mass due to T-pion channels!

One T-pion VBF: the Y_Q=1/6 case

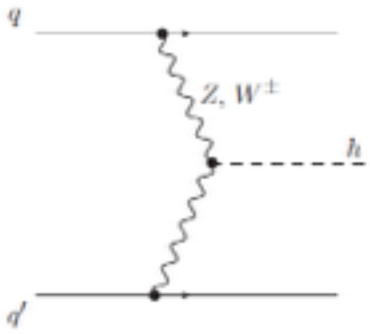


Parton level

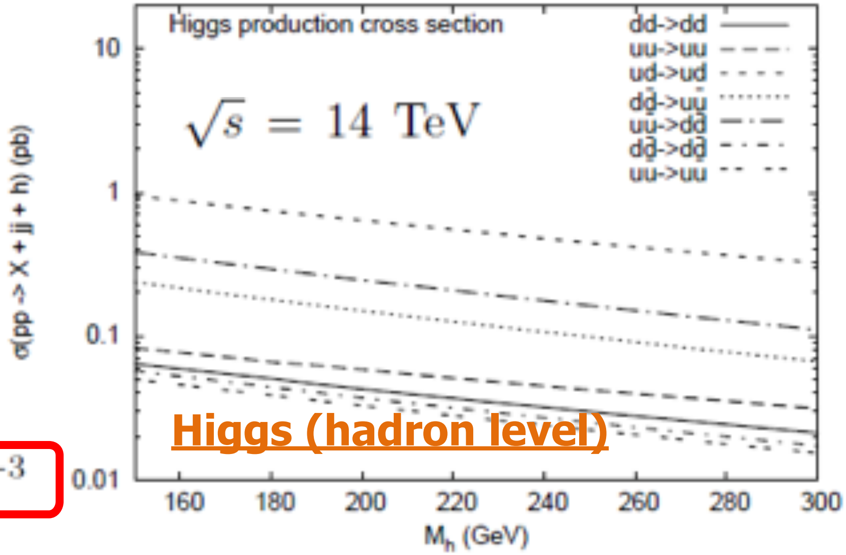


Hadron level

Born-induced!

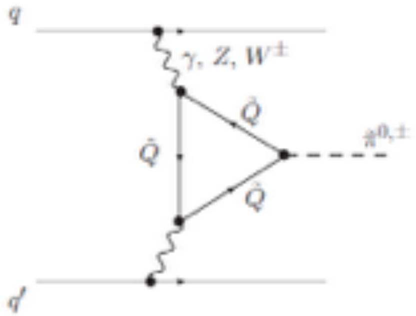


$$\mathrm{BR}(h \to \gamma\gamma) \simeq 10^{-3}$$



Higgs (hadron level)

Loop-induced!



$$\mathrm{BR}(\tilde{\pi} \to \gamma\gamma) \simeq 0.5 - 1.0$$

Higgs VBF and T-pion γγ yields may be comparable for light Tpions!

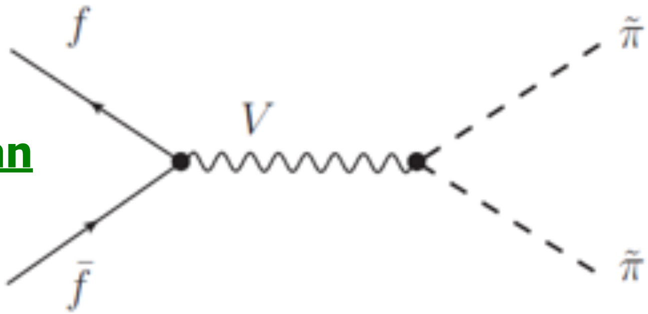
T-pion pair production in the VLTC: contributions

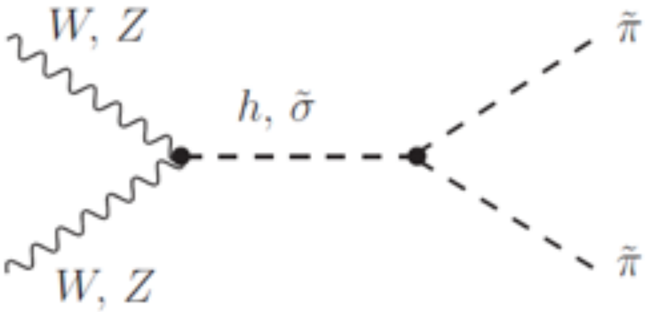
Born-induced at the LO!

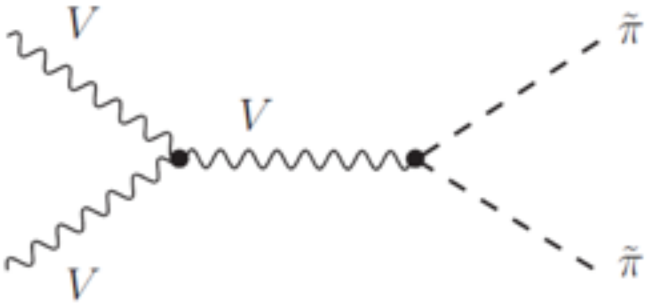
Dominates!

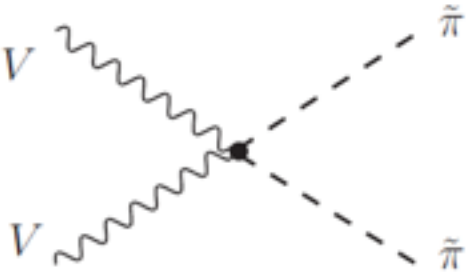
BUT! No resonance…

Drell-Yan

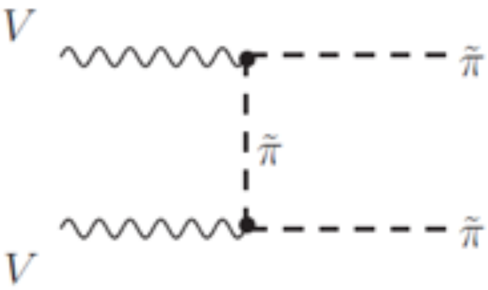








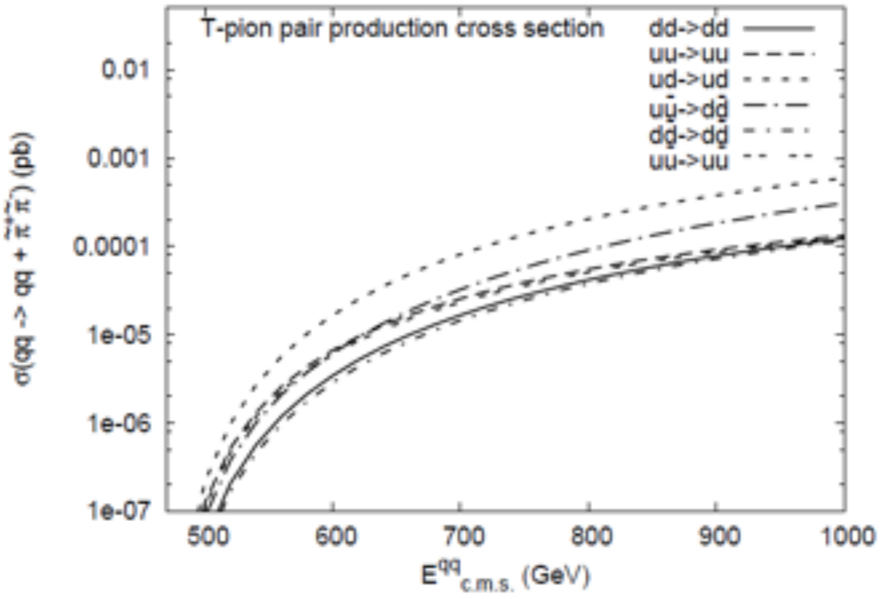
VBF

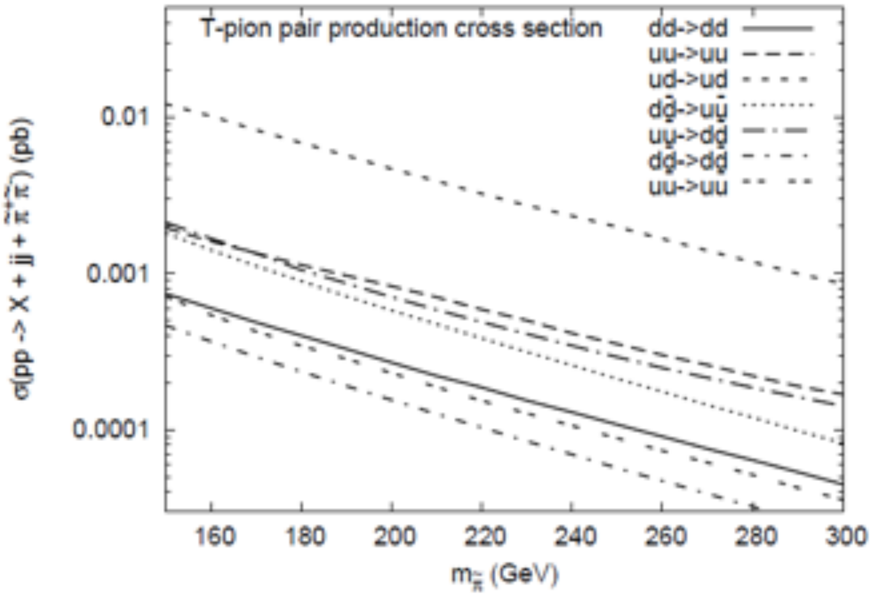


Similar for scalar T-baryons!

Four or six (!) gauge boson signatures!

T-pion pair production: VBF mechanism





T-pion pair

- ➢ Similar to one-pion cross sections at large x
- ➢ Multi-lepton/multi-jet/multi-gamma final states
- ➢ No two-pion resonance (very wide sigma)

T-baryon pair
(in prospects..)

- ➢ recharge of B_0 in detector (displaced vertices)
- ➢ Asymmetry in ET_{mis}

Discussions

- The VLTC with light T-pions and T-sigma has been studied. As a possible source of dynamical EWSB, it effectively preserves the standard Higgs mechanism of the SM and evades EW precision tests

- The model is consistent with SM-like Higgs observations but can explain small deviations in Higgs couplings if confirmed by experiment

- The model provides rich TC phenomenology at the LHC by means of T-pions/T-sigma and possibly T-baryons production and decays

- Scalar vector-like T-baryons may play an important role in astrophysics as components of the Dark Matter evading the most stringent SI scattering data unlike fermionic T-neutron of QCD type if T-baryon number is conserved. This determines the choice of SU(2)TC confinement group

- Trivial extension of the minimal VLTC by means of weak-singlet Tquarks and hybrid color-TC reps enables to construct composite 2HDM with one lightest Higgs boson and gives rise to partial lepton compositeness and dynamical "see-saw" mechanism for neutrino mass generation.

- VLTC is simple but will require a large effort to be found/ruled out