Dark Matter carriers from vector-like Technicolor model

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QFTHEP-2015
Samara
Dynamical EWSB (Higgsless models):

- TC was introduced as the mechanism for DEWSB via a condensate of technifermions (techniquarks) $\langle \bar{F} F \rangle$
- Technifermions are charged under $SU(N)_{TC}$
- TC condensate breaks symmetry $SU(2)_W \otimes U(1)_Y$ to $U(1)_{em}$ without fundamental Higgs.

(Susskind 1979, Weinberg 1979, Farhi and Jackiw 1982 etc)

New dynamics with strong coupling – new confinement scale
- composite(?) Higgs – extra T-hadron states – composite(?) Dark Matter

QCD: hadrons and constituent quarks
TC: T-hadrons and constituent T-quarks

Linear $\sigma$ (T-$\sigma$) Model:
- constituent quark (T-quark) – meson (T-meson) interactions

$N, Q, \sigma, \pi, \omega, \rho, f, a, \ldots$  $\tilde{N}, \tilde{Q}, \tilde{\sigma}, \tilde{\pi}, \tilde{\omega}, \tilde{\rho}, \tilde{f}, \tilde{a}, \ldots$
Static properties of light hadrons can be completely determined by two dimensionful vacuum parameters:

**QCD**

\[ \Lambda_{QCD} \sim 200 \text{ MeV} \]

**gluon condensate:**

\[ \langle 0 \mid \frac{\alpha_s}{\pi} \hat{G}_{\mu\nu} \hat{G}^{\mu\nu} \mid 0 \rangle = (365 \pm 20 \text{ MeV})^4 \approx (2\Lambda_{QCD})^4, \]

\[ \langle 0 \mid \bar{u}u \mid 0 \rangle = \langle 0 \mid \bar{d}d \mid 0 \rangle = -l_g \langle 0 \mid \frac{\alpha_s}{\pi} \hat{G}_{\mu\nu} \hat{G}^{\mu\nu} \mid 0 \rangle = -(235 \pm 15 \text{ MeV})^3 \]

**light quark condensate:**

**QCD – T-QCD analogy**

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

\[ \langle 0 \mid \frac{\alpha_{TC}}{\pi} \hat{F}_{\mu\nu} \hat{F}^{\mu\nu} \mid 0 \rangle \sim (2\Lambda_{TC})^4, \]

\[ \langle 0 \mid \bar{U}U \mid 0 \rangle = \langle 0 \mid \bar{D}D \mid 0 \rangle \sim -l_{TC}(2\Lambda_{TC})^4 \]

**New strong coupling scale, \( \Lambda_{TC} \):**

\[ \Lambda_{TC} \gtrsim \nu \sim 200 \text{ GeV} \]

**“T-QCD”**
Simplest scenario: two-color bosonic TC with two generations of chiral fields

Consider the following case:

Left chiral quark doublet charges: \( q_{U,D} = \pm 1/2 \)

Electro-weak singlets hypercharges: \( Y = \pm 1/2 \)

Right chiral TC-field are SU(2)\(_L\) singlets
Left bidoublet transformation:

\[
(Q^{a\alpha}_L(A))' = Q^{a\alpha}_L(A) + \frac{i}{2} g_W \theta_k \tau^{ab}_k Q^{b\alpha}_L(A) + \frac{i}{2} g_T C \phi_k \tau^{\alpha\beta}_k Q^{a\beta}_L(A)
\]

Right field transformation:

\[
(U^{\alpha}_R)' = U^{\alpha}_R + \frac{i}{2} g_1 \theta U^{\alpha}_R + \frac{i}{2} g_T C \phi_k \tau^{\alpha\beta}_k U^{\beta}_R;
\]

\[
(D^{\alpha}_R)' = D^{\alpha}_R - \frac{i}{2} g_1 \theta D^{\alpha}_R + \frac{i}{2} g_T C \phi_k \tau^{\alpha\beta}_k D^{\beta}_R
\]
SU(2)_L \times SU(2)_R \times L(T)\sigma M

1-st TC-quark generation

\[ Q_{L(1)} = (U_{L(1)}, D_{L(1)}), U_{R(1)}, D_{R(1)} \]

2-nd TC-quark generation

Charge conjugation

\[ \hat{C}Q^{a\alpha}_{L(2)} = Q^{\dagger C a\alpha}_{L(2)} \]

Now the field transforms as

\[ (Q^{C a\alpha}_{L(2)})' = Q^{C a\alpha}_{L(2)} - \frac{i}{2}g_W \theta_k (\tau^a_k)Q^{C b\alpha}_{L(2)} - \frac{i}{2}g_{TC} \phi_k (\tau^{\alpha\beta}_k)Q^{C a\beta}_{L(2)} \]

New right-handed weak doublet

\[ Q^{\alpha\alpha}_{R(2)} = \varepsilon^{ab} \varepsilon^{\alpha\beta} Q^{Cb\beta}_{L(2)}, \quad \varepsilon = i\sigma_2 \]
Right-handed field of 2-nd generation transforms as corresponding left handed field

\[ (Q^{a\alpha}_{R(2)})' = Q^{a\alpha}_{R(2)} + \frac{i}{2} g_w \theta_k \tau^a_{k} Q^{b\alpha}_{R(2)} + \frac{i}{2} g_{TC} \varphi_k \tau^a_{k} Q^{a\beta}_{R(2)} \]

Composing these fields \quad \rightarrow \quad \text{Dirac weak doublet}

\[ Q^{a\alpha} = Q^{a\alpha}_{L(1)} + Q^{a\alpha}_{R(2)} = Q^{a\alpha}_{L(1)} + \epsilon^{ab} \epsilon^{\alpha\beta} Q^{Cb\beta}_{L(2)} \]

Having two right-handed fields \quad \rightarrow \quad \text{Dirac TC-field, SU(2)\text{\textsubscript{L}} scalar}

\[ (D^{\alpha}_{L})' = D^{\alpha}_{L} - \frac{i}{2} g_1 \theta D^{\alpha}_{L} + \frac{i}{2} g_{TC} \varphi_k \tau^\alpha_{k} D^\beta_{L} \]

\[ S^{\alpha} = D^{\alpha}_{L} + D^{\alpha}_{R} = -\epsilon^{\alpha\beta} U^{C\beta}_{R} + D^{\alpha}_{R} \]
Simplest vector-like TC SU(2)\(_L\) \(\times\) SU(2)\(_R\) Lagrangian (with extra weak singlet quark S for composite scalar “Higgs boson”) 

\[
L(T, Q, S) = -\frac{1}{4} T_{\mu\nu} T_{\mu\nu}^n + i \bar{Q} \gamma^\mu (\partial_\mu - \frac{i}{2} g_W W^a_\mu \tau_a - \frac{i}{2} g_{TC} T^n_\mu \tau_n) Q - m_Q \bar{Q} Q \\
+ i \bar{S} \gamma^\mu (\partial_\mu + \frac{i}{2} g_1 B_\mu - \frac{i}{2} g_{TC} T^n_\mu \tau_n) S - m_S \bar{S} S.
\]

**LT\(\sigma\)M** – \(\sigma\)-field interaction with T-degrees of freedom (cf. low-energy quark-meson interactions) 

\[
\bar{Q} Q \rightarrow \langle \bar{Q} Q \rangle + \bar{Q} Q
\]

Scalar real field \(S' = <S'> + \sigma\) (non-zero v.e.v.), \(<S'> \equiv u\) gives masses for T-quarks

\[
-g_{TC} \left( \langle \bar{Q} Q \rangle S + \bar{Q} (S + i \gamma_5 P^a \tau^a) Q \right)
\]

- **scalar T-sigma** (singlet rep.)
- **pseudoscalar T-pions** (adjoint rep.)

**T-\(\sigma\)-meson** – lightest T-glueball? 
**T-pions** – T-quark condensate excitation?
Both $u$ and $v$ v.e.v.’s are induced by T-quark condensate

$$u, v \sim \sqrt[3]{\langle \bar{Q}Q \rangle}$$

Vacuum potential energy

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

some $h - \sigma$ mixing is due to $\mathcal{H}$ - scalar Higgs doublet

Possible deviations from the SM for $\lambda \neq 0$?

Here we consider the simplest TC model variant: $N_c=2$, $q_{U,D} = \pm 1/2$

The model Lagrangian
T-quark – vector bosons interaction

\[ L(Q, G) = \frac{1}{\sqrt{2}} g \bar{U} \gamma^\mu DW_\mu^+ + \frac{1}{\sqrt{2}} g \bar{D} \gamma^\mu UW_\mu^- \\
+ \frac{1}{2} g (\bar{U} \gamma^\mu U - \bar{D} \gamma^\mu D)(c_w Z_\mu + s_w A_\mu) \]

T-pions – vector bosons interaction

\[ L(\pi, G) = ig W^{\mu+} (\pi^0 \pi^- - \pi^- \pi^0) + ig W^{-\mu} (\pi^+ \pi^0 - \pi^0 \pi^+) \\
+ ig (c_w Z_\mu + s_w A_\mu) \ast (\pi^- \pi^+ - \pi^+ \pi^-) + g^2 W^{\mu+} W^{-\mu} (\pi^0 \pi^0 + \pi^+ \pi^-) \\
+ g^2 (c_w Z_\mu + s_w A_\mu)^2 \ast \pi^+ \pi^- + ... \]

T-quarks – (pseudo-) scalar field interaction

\[ L(Q, \sigma, h) = - g_{TC} (c_\theta \sigma + s_\theta h) \ast (\bar{U} U + \bar{D} D) - i \sqrt{2} g_{TC} \pi^+ \bar{U} \gamma_5 D \\
- i \sqrt{2} g_{TC} \pi^- \bar{D} \gamma_5 U - i \sqrt{2} g_{TC} \pi^0 (\bar{U} \gamma_5 U - \bar{D} \gamma_5 D). \]
Oblique corrections (Peskin – Takeuchi parameters) – New Physics should not drastically change EW observables!

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

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

\[ \Gamma_Z = \frac{M_Z^3 \beta_Z}{1 - \hat{\alpha}(M_Z)T} \]

Precision exp. constraints

\[ S = 0.00^{+0.11}_{-0.10} \quad T = 0.02^{+0.11}_{-0.12} \quad U = 0.08 \pm 0.11 \]

\[ \alpha S = 4s_w^2c_w^2 \left[ \frac{\Pi_{ZZ}(M_Z^2)}{M_Z^2} - \frac{c_w^2 - s_w^2}{s_w c_w} \Pi'_{Z\gamma}(0) - \Pi'_{\gamma\gamma}(0) \right] \]

\[ \alpha U = 4s_w^2 \left[ \frac{\Pi_{WW}(M_W^2)}{M_W^2} - \frac{c_w^2 \Pi_{ZZ}(M_Z^2)}{M_Z^2} - 2s_w c_w \Pi'_{Z\gamma}(0) - s_w^2 \Pi'_{\gamma\gamma}(0) \right] \]

\[ \alpha T = \frac{\Pi_{WW}(0)}{M_W^2} - \frac{\Pi_{ZZ}(0)}{M_Z^2} \]
SU(2)_L x SU(2)_R: oblique corrections diagrams

Structure of P-T parameters in the model

\[ \Pi_{XY}(p^2) = \frac{g^2}{24\pi^2} K_{XY} \left[ F_\pi(p^2) + N_C F_Q(p^2) \right] \]

\[ X, Y = W, Z, \gamma. \]
In the case of zero “higgs – T-sigma” mixing!

\[ \beta_{W,Z}^\pi = \frac{4m^2_W}{M^2_{W,Z}} - 1 > 0, \quad \beta_{Q}^{W,Z} = \frac{4m_Q^2}{M^2_{W,Z}} - 1 > 0. \]

\[ S = \frac{2c_w^4}{3\pi} \left\{ \frac{1}{3} - \beta_{\pi}^Z (1 - \sqrt{\beta_{\pi}^Z} \arctg \frac{1}{\sqrt{\beta_{\pi}^Z}}) + N_C \left[ -\frac{1}{3} + (3 + \beta_{Q}^Z) * (1 - \sqrt{\beta_{Q}^Z} \arctg \frac{1}{\sqrt{\beta_{Q}^Z}}) \right] \right\} \]

\[ U = \frac{2}{3\pi} \left\{ \frac{1}{3} (1 - c_w^4) * (1 - N_C) - \beta_{\pi}^W (1 - \sqrt{\beta_{\pi}^W} \arctg \frac{1}{\sqrt{\beta_{\pi}^W}}) \right. \\
\left. + N_C [(3 + \beta_{Q}^W) * (1 - \sqrt{\beta_{Q}^W} \arctg \frac{1}{\sqrt{\beta_{Q}^W}}) + c_w^4 \beta_{Q}^Z (1 - \sqrt{\beta_{Q}^Z} \arctg \frac{1}{\sqrt{\beta_{Q}^Z}}) - c_w^4 (3 + \beta_{Q}^Z) * (1 - \sqrt{\beta_{Q}^Z} \arctg \frac{1}{\sqrt{\beta_{Q}^Z}})] \right\} \]

\[ \Pi_{WW}(0) = \Pi_{ZZ}(0) = 0 \rightarrow T = 0 \]
P-T parameters $S$ and $U$ as functions of T-pion mass and T-quark mass

Remind that

\[
S = 0.00^{+0.11}_{-0.10} \quad T = 0.02^{+0.11}_{-0.12} \quad U = 0.08 \pm 0.11
\]
Deviations of the Higgs properties from the SM are so much the less, the smaller is the $\Delta m_\sigma$.

$T$-sigma – T-pion parameter

$\Delta m_\sigma = m_\sigma - \sqrt{3} m_\pi$

$m_{\tilde{\pi}}$, $m_{\tilde{\sigma}}$ are free parameters of the model

Should $\Delta m_\sigma$ be small?

Deviations of the Higgs properties from the SM are so much the less, the smaller is the $\Delta m_\sigma$.
Diquark-like bound states with conserved T-baryonic number, $T_B$

\[
\begin{align*}
B^+ &= UU, & B^- &= DD, & B^0 &= UD, & T_B &= +1, \\
\bar{B}^+ &= \bar{U}\bar{U}, & \bar{B}^- &= \bar{D}\bar{D}, & \bar{B}^0 &= \bar{U}\bar{D}, & T_{\bar{B}} &= -1.
\end{align*}
\]

T-baryon interactions with the SM vector bosons

no vector interactions of type \( \bar{B}^0 B^0 Z \).

\[
\mathcal{L}_{VBB} = ig \left[ W_{\mu}^- (B^0_{,\mu} \bar{B}^- - B^0 \bar{B}^-_{,\mu} + \bar{B}^0_{,\mu} B^+ - \bar{B}^0 B^+_{,\mu}) \\
+ (s_W A_{\mu} + c_W Z_{\mu}) (B^+_{,\mu} \bar{B}^+ - \bar{B}^-_{,\mu} B^-) \right] + c.c.
\]

\[
\mathcal{L}_{VVBB} = g^2 \left[ (\bar{B}^0 B^0 + \bar{B}^+ B^+) W^{+\mu} W^{\mu-} \\
+ \bar{B}^+ B^+ (s_W A_{\mu} + c_W Z_{\mu})^2 - \bar{B}^+ B^- W^{+\mu} W^{\mu+} \\
- (\bar{B}^+ B^0 + \bar{B}^0 B^-) (s_W A_{\mu} + c_W Z_{\mu}) W^{+\mu} + c.c. \right]
\]

+ T-baryons interactions with Higgs boson, T-pions, T-sigma

Lightest state of B-triplet -> scalar T-baryon DM?

(see report of M.Bezuglov)
Intermediate conclusions

• Dynamical EWSB in VLTC provides an effective Higgs mechanism, induced by T-fermion condensate at high-energy TC-scale;

• It is shown how TC-model can be rearranged as the model with vector-like interaction of T-quarks with SM vector bosons;

• Such vector-like two-boson TC model with SU(2) symmetry has no problems with the EW (and FCNC) precision constraints, conserving standard Higgs mechanism;

• Light T-pions and T-sigma as carriers of new strong TC-dynamics can emerge at the LHC energies through their creation and decays; the amplitude of Higgs – T-sigma mixing drive possible non-SM Higgs behavior; +T-loops contributions!

• TC-model can be formulated as higgsless too – due to extra weak singlet T-quark, keeping all important features: safety for P-T parameters, a rich phenomenology of (pseudo)scalar states, small deviations from the SM “Higgs state” and so on;

• In all variants TC-model contains some lightest neutral states, which are good candidates for the CDM description – here it is one of the component of triplet of bounded di(T)quark states with conserved T-baryon number. Analysis of this possibility will be presented in the report of M.Bezuglov.
Thank you for attention!
References

Receipt of right-handed component

\[
\epsilon^{ab}\epsilon^{\alpha\beta}(Q^{\mathbb{C}b\beta}_{L(2)})' = \epsilon^{ab}\epsilon^{\alpha\beta}Q^{\mathbb{C}b\beta}_{L(2)} - \frac{\imath}{2}g_{W}\theta_{k}\epsilon^{ab}(\tau^{bc}_{k})^{*}\epsilon^{\alpha\beta}Q^{\mathbb{C}c\beta}_{L(2)}
\]
\[- \frac{\imath}{2}g_{TC}\varphi_{k}\epsilon^{\alpha\beta}(\tau^{\beta\gamma}_{k})^{*}\epsilon^{ab}Q^{\mathbb{C}b\gamma}_{L(2)}.
\]

\[
\epsilon^{\gamma\mu}\epsilon^{\lambda\mu} = \delta^{\gamma\lambda}
\]
\[
\epsilon^{ef}\epsilon^{df} = \delta^{cd}
\]

\[
\epsilon^{ab}\epsilon^{\alpha\beta}(Q^{\mathbb{C}b\beta}_{L(2)})' = \epsilon^{ab}\epsilon^{\alpha\beta}Q^{\mathbb{C}b\beta}_{L(2)} - \frac{\imath}{2}g_{W}\theta_{k}\epsilon^{ab}(\tau^{bc}_{k})^{*}\epsilon^{\alpha\beta}Q^{\mathbb{C}c\beta}_{L(2)}
\]
\[- \frac{\imath}{2}g_{TC}\varphi_{k}\epsilon^{\alpha\beta}(\tau^{\beta\gamma}_{k})^{*}\epsilon^{ab}Q^{\mathbb{C}b\gamma}_{L(2)}.
\]

\[
\epsilon^{ab}(\tau^{bc}_{k})^{*}\epsilon^{ef} = \tau^{af}_{k}, \quad \epsilon^{\alpha\beta}(\tau^{\beta\gamma}_{k})^{*}\epsilon^{\gamma\mu} = \tau^{\alpha\mu}_{k}.
\]

+antisymmetry of epsilon matrices

\[
(Q^{a\alpha}_{R(2)})' = Q^{a\alpha}_{R(2)} + \frac{\imath}{2}g_{w}\theta_{k}\tau^{ab}_{k}Q^{b\alpha}_{R(2)} + \frac{\imath}{2}g_{TC}\varphi_{k}\tau^{\alpha\beta}_{k}Q^{a\beta}_{R(2)}.
\]
T-parameter: constraint on $\phi h$-mixing and $\sigma$-mass

RP et al, PRD88, 075009 (2013)

a small mixing angle and/or small $\sigma$-mass are preferable!
Constraints on 2BTCM: FCNC processes

One-loop SM part

Extra contributions

New TC contributions to FCNC’s are strongly suppressed:

• Two-loop FCNC effects
• heavy $\sigma$ –mass in denominators
• double suppression by a small $\sigma$-Higgs mixing