Minimal Walking Technicolor for Colliders

Mads Toudal Frandsen
toudal@nbi.dk

University of Southern Denmark and The Niels Bohr Institute

R. Foadi, M.T.F, T. Ryttov, F. Sannino; arXiv:0706.1696v1
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Outline

1. Technicolor
   - Challenges: EWPD and FCNC's
   - Walking Can Help

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2. Minimal Walking Technicolor Model (MWT)
   - Underlying Theory
   - Effective Theory
     - Spectrum
     - A Comprehensive Low-Energy Lagrangian for MWT
     - Weinberg Sum Rules and Walking in the effective Lagrangian
     - Dark Matter

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3. Summary and Projects
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Dynamical EW Symmetry Breaking

- New Standard Model Fermions

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Technicolor

New Strong Interaction at ~ 250 GeV Weinberg, Susskind

Augment the Standard Model Gauge Group

$$SU(N)_{TC} \times SU(3)_C \times SU(2)_L \times U(1)_Y \tag{1}$$

The chiral condensate is responsible for EWSB

$$< Q_f \bar{Q}^{f'} > \sim \Lambda_{TC}^3 \delta_f^{f'} \ , \qquad \Lambda_{TC} \sim 250 GeV \tag{2}$$

S parameter and Flavor Changing Neutral Currents

S parameter

$$S = -16\pi \frac{\Pi_{3Y}(M_Z^2) - \Pi_{3Y}(0)}{M_Z^2} \tag{3}$$

The perturbative techniquark contribution (deg. isodublet) is

$$S_{Pert} = \frac{1}{6\pi}\frac{N_f}{2} d(R) \ , \qquad S_{TC} > S_{Pert} \tag{4}$$

S is large in QCD like theories [Peskin, Takeuchi]

S parameter and Flavor Changing Neutral Currents

Fermion Masses and Flavor Changing Neutral Currents

- ETC interactions generate fermion masses and introduce potential FCNC's

$$\beta_{ab}\frac{\bar{Q}_L T^a Q_R \bar{\psi}_R T^b \psi_L}{\Lambda_{ETC}^2} + \gamma_{ab}\frac{\bar{\psi}_L T^a \psi_R \bar{\psi}_R T^b \psi_L}{\Lambda_{ETC}^2} + \ldots \tag{5}$$

- Suppression of FCNC's require a large scale separation

$$\Lambda_{ETC} >> \Lambda_{TC} \sim 250 GeV \tag{6}$$

- Mass generation requires enhancement of condensate at Λ_{ETC}

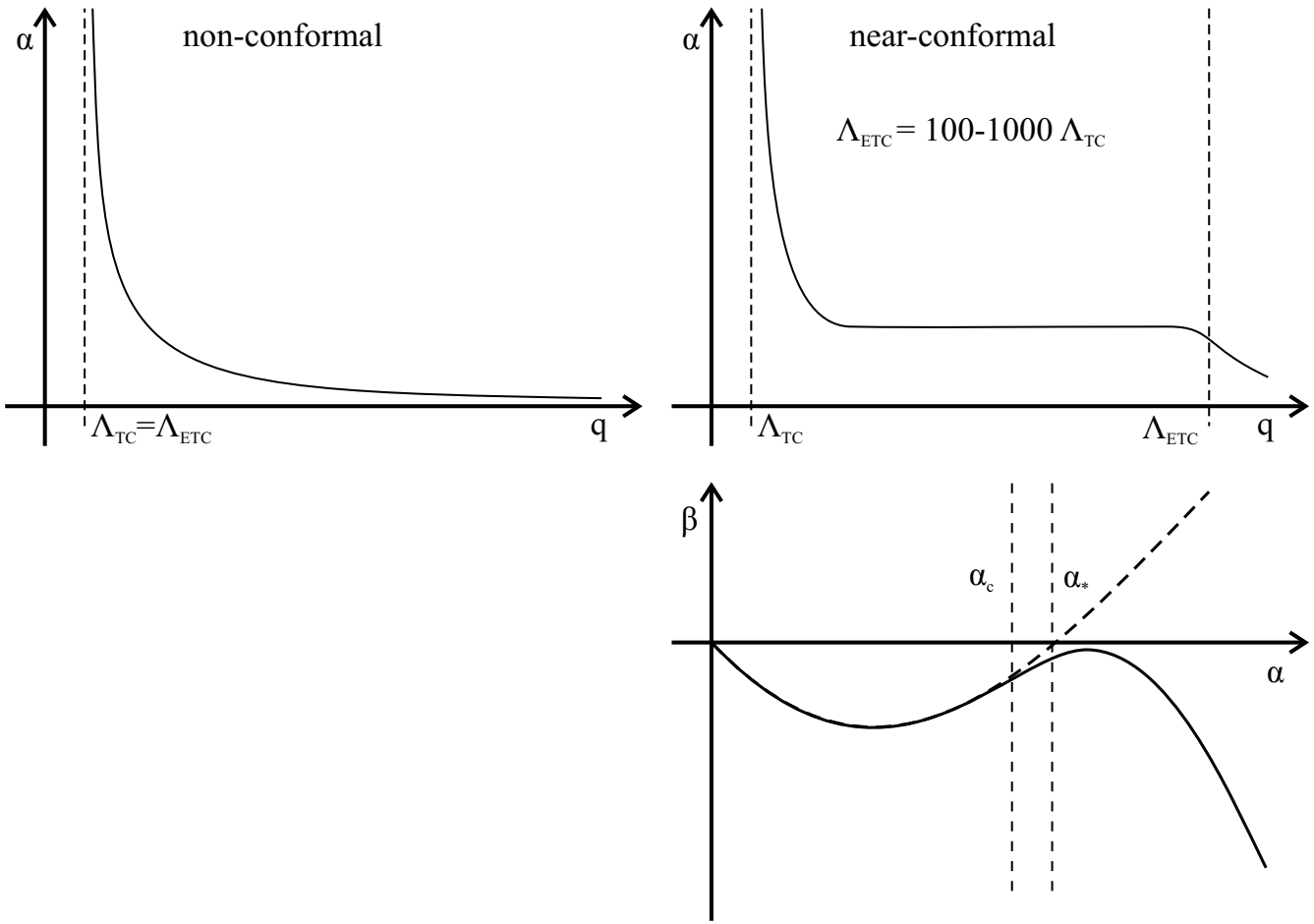
$$< \bar{Q}Q >_{ETC} \tag{7}$$

Walking can help

- Walking dynamics can provide a scale separation $\Lambda_{ETC} > \Lambda_{TC}$ and condensate enhancement.

  Holdom[85]; Appelquist-Karabali-Wijewardhana[86];...
- Walking Dynamics can provide a lower estimate for S.
  Holdom-Terning [90], Sundrum-Hsu [96], Knecht-De Rafael [97], Appelquist-Sannino [98]

Walking vs. Running coupling constant



S in Walking Technicolor

S in Walking Technicolor

$$S_{WTC} < S_{Pert} \tag{8}$$

$$S = (\frac{1}{6\pi} - \delta) d(R) \frac{N_f}{2} \tag{9}$$

Also new Leptons can lower S_{Pert}

The Minimal Walking Technicolor Model

- Underlying Theory

  Sannino-Tuominen[04], Dietrich-Sannino-Tuominen[05], Dietrich-Sannino[06]
- Effective Theory

  Foadi-M.T.F-Ryttov-Sannino [07]

Underlying Theory

Particle Content

- Techniquarks in the 2S=Adj Rep of $SU(2)_{TC}$

$$Q_L^a = \begin{pmatrix} U^a \\ D^a \end{pmatrix}_L , \qquad U_R^a , \quad D_R^a , \qquad a = 1, 2, 3 ,$$

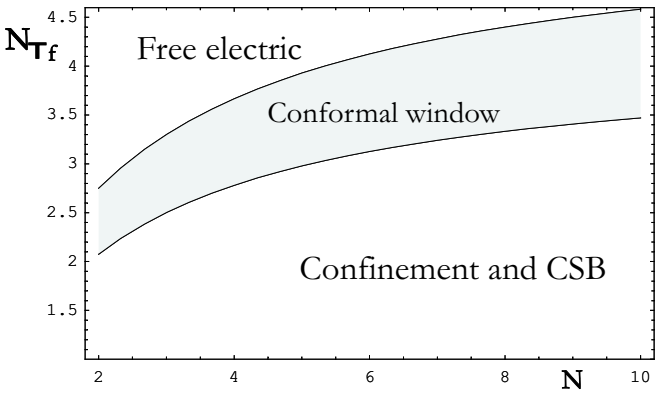
- A new Lepton generation to avoid global Witten Anomaly

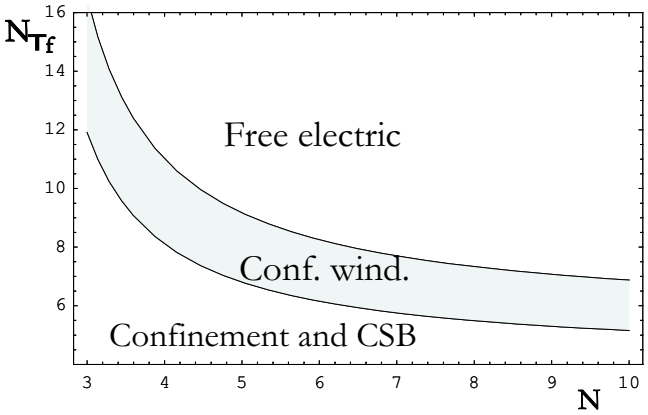
$$\begin{pmatrix} N \\ E \end{pmatrix}_L , \qquad N_R , \; E_R \tag{10}$$

- The most general anomaly free hypercharge assignment

$$\begin{aligned} Y(Q_L) &= \frac{y}{2} , \quad Y(U_R, D_R) = (\frac{y+1}{2}, \frac{y-1}{2}) \\ Y(L_L) &= -3\frac{y}{2} , \quad Y(N_R, E_R) = (\frac{-3y+1}{2}, \frac{-3y-1}{2}). \end{aligned} \tag{11}$$

MWT is close to the conformal window





$S \sim 0.1$ for MWT

Effective Theory

Flavor Symmetries

- Enhanced Flavor Symmetries since 2S=Adj is a real rep. of $SU(2)_{TC}$

$$Q = \begin{pmatrix} U_L \\ D_L \\ \epsilon U_R^* \\ \epsilon D_R^* \end{pmatrix} , \tag{12}$$

- Assuming maximally preserved flavor symmeries

$$SU(4) \rightarrow SO(4)$$
$$< Q_i^\alpha Q_j^\beta \epsilon_{\alpha\beta} E^{ij} > = -2 < \bar{U}_R U_L + \bar{D}_L D_R > \tag{13}$$

Effective Theory

Linear Realization

- 4x4 Hermitean Matrix of composite (pseudo-)scalars

$$M_{ij} \sim Q_i^\alpha Q_j^\beta \varepsilon_{\alpha\beta} \qquad \text{with } i,j = 1\ldots 4. \tag{14}$$

- 4x4 Matrix Hermitean traceless matrix of composite vectors

$$A_i^{\mu,j} \sim \; Q_i^\alpha \sigma^\mu_{\alpha\dot\beta} \bar{Q}^{\dot\beta,j} - \frac{1}{4}\delta_i^j Q_k^\alpha \sigma^\mu_{\alpha\dot\beta} \bar{Q}^{\dot\beta,k} \; . \tag{15}$$

Scalars

$$M = \begin{pmatrix} i\Pi_{UU} + \widetilde{\Pi}_{UU} & \frac{i\Pi_{UD} + \widetilde{\Pi}_{UD}}{\sqrt{2}} & \frac{\sigma + i\Theta + i\Pi^0 + A^0}{2} & \frac{i\Pi^+ + A^+}{\sqrt{2}} \\ \frac{i\Pi_{UD} + \widetilde{\Pi}_{UD}}{\sqrt{2}} & i\Pi_{DD} + \widetilde{\Pi}_{DD} & \frac{i\Pi^- + A^-}{\sqrt{2}} & \frac{\sigma + i\Theta - i\Pi^0 - A^0}{\sqrt{2}} \\ \frac{\sigma + i\Theta + i\Pi^0 + A^0}{2} & \frac{i\Pi^- + A^-}{\sqrt{2}} & i\Pi_{\overline{UU}} + \widetilde{\Pi}_{\overline{UU}} & \frac{i\Pi_{\overline{UD}} + \widetilde{\Pi}_{\overline{UD}}}{\sqrt{2}} \\ \frac{i\Pi^+ + A^+}{\sqrt{2}} & \frac{\sigma + i\Theta - i\Pi^0 - A^0}{2} & \frac{i\Pi_{\overline{UD}} + \widetilde{\Pi}_{\overline{UD}}}{\sqrt{2}} & i\Pi_{\overline{DD}} + \widetilde{\Pi}_{\overline{DD}} \end{pmatrix}$$

Vectors

$$A^\mu = \begin{pmatrix} \frac{a^{0\mu} + v^{0\mu} + v^{4\mu}}{2\sqrt{2}} & \frac{a^{+\mu} + v^{+\mu}}{2} & \frac{x^\mu_{UU}}{\sqrt{2}} & \frac{x^\mu_{UD} + s^\mu_{UD}}{2} \\ \frac{a^{-\mu} + v^{-\mu}}{2} & \frac{-a^{0\mu} - v^{0\mu} + v^{4\mu}}{2\sqrt{2}} & \frac{x^\mu_{UD} - s^\mu_{UD}}{2} & \frac{x^\mu_{DD}}{\sqrt{2}} \\ \frac{x^\mu_{UU}}{\sqrt{2}} & \frac{x^\mu_{UD} - s^\mu_{UD}}{2} & \frac{a^{0\mu} - v^{0\mu} - v^{4\mu}}{2\sqrt{2}} & \frac{a^{-\mu} - v^{-\mu}}{2} \\ \frac{x^\mu_{UD} + s^\mu_{UD}}{2} & \frac{x^\mu_{DD}}{\sqrt{2}} & \frac{a^{+\mu} - v^{+\mu}}{2} & \frac{-a^{0\mu} + v^{0\mu} - v^{4\mu}}{2\sqrt{2}} \end{pmatrix}$$

Fermions and Electroweak Gauge Bosons

In addition to the standard model fields there is an SU(4) multiplet for the new leptons and the dressed techniquarks,

$$L = \begin{pmatrix} N_L \\ E_L \\ \epsilon {N_R}^* \\ \epsilon {E_R}^* \end{pmatrix} \quad , \quad \widetilde{Q} = \begin{pmatrix} \widetilde{U}_L \\ \widetilde{D}_L \\ \epsilon \widetilde{U}_R^* \\ \epsilon \widetilde{D}_R^* \end{pmatrix} \quad . \tag{16}$$

Finally we have the embedding of electroweak gauge bosons

$$G_\mu(y) = \begin{pmatrix} W_\mu & 0 \\ 0 & -\frac{g_1}{2g_2} B_\mu \tau^3 \end{pmatrix} + y \frac{g_1}{2g_2} B_\mu \begin{pmatrix} 1 & 0 \\ 0 & -1 \end{pmatrix} \tag{17}$$

The Low-Energy Lagrangian for MWT

Define the covariant derivative and vector field

$$\begin{aligned} D_\mu M &= \partial_\mu M - i\, g_2 \left[G_\mu(y) M + M G_\mu^T(y) \right] \\ C_\mu &\equiv A_\mu - \frac{g_2}{\tilde{g}}\, G_\mu(y) \end{aligned} \tag{18}$$

We write the following Lagrangian

$$\begin{aligned} \mathcal{L} &= \mathcal{L}_{\text{Higgs}} + \mathcal{L}_{\text{Kinetic}} + \mathcal{L}_{\text{C}} + \mathcal{L}_{\text{ETC}} \\ \mathcal{L}_{\text{Higgs}} &= \frac{1}{2}\text{Tr}\left[D_\mu M D^\mu M^\dagger \right] - \mathcal{V}(M) + \mathcal{L}_{\text{ETC}} \\ \mathcal{L}_{\text{kinetic}} &= -\frac{1}{2}\text{Tr}\left[\widetilde{W}_{\mu\nu} \widetilde{W}^{\mu\nu} \right] - \frac{1}{4} B_{\mu\nu} B^{\mu\nu} - \frac{1}{2}\text{Tr}\left[F_{\mu\nu} F^{\mu\nu} \right] + m_A^2\ \text{Tr}\left[C_\mu C^\mu \right] \\ \mathcal{L}_{\text{M-C}} &= \tilde{g}^2\ r_1\ \text{Tr}\left[C_\mu C^\mu M M^\dagger \right] + \tilde{g}^2\ r_2\ \text{Tr}\left[C_\mu M C^{\mu\, T} M^\dagger \right] \\ &+ i\ \tilde{g}\ r_3\ \text{Tr}\left[C_\mu \left(M (D^\mu M)^\dagger - (D^\mu M) M^\dagger \right) \right] \\ &+ \tilde{g}^2\ s\ \text{Tr}\left[C_\mu C^\mu \right] \text{Tr}\left[M M^\dagger \right] \ . \end{aligned} \tag{19}$$

The Weinberg Sum Rules

Weinberg Sum Rules in QCD-like theories

- $$i\Pi(q^2) \equiv \int d^4x\, e^{-iqx} \left[< J_V(x) J_V(0) > - < J_A(x) J_A(0) > \right] \,, \tag{20}$$
- In QCD Weinberg Sum rules + Vector Dominance gives

$$F_V^2 - F_A^2 = F_\pi^2 \,, \qquad F_V^2 M_V^2 - F_A^2 M_A^2 = 0 \tag{21}$$

The Weinberg Sum Rules

Weinberg Sum Rules in Walking Theories

- Only second Sum Rule is affected by near conformal region
  Appelquist, Sannino [98]

$$F_V^2 M_V^2 - F_A^2 M_A^2 = a \frac{8\pi^2}{d(R)} F_\pi^4, \tag{22}$$

- a is a non-universal quantity and we expect $a \sim O(1)$

Constraining the Effective Theory

- The effective lagrangian contains a number of parameters

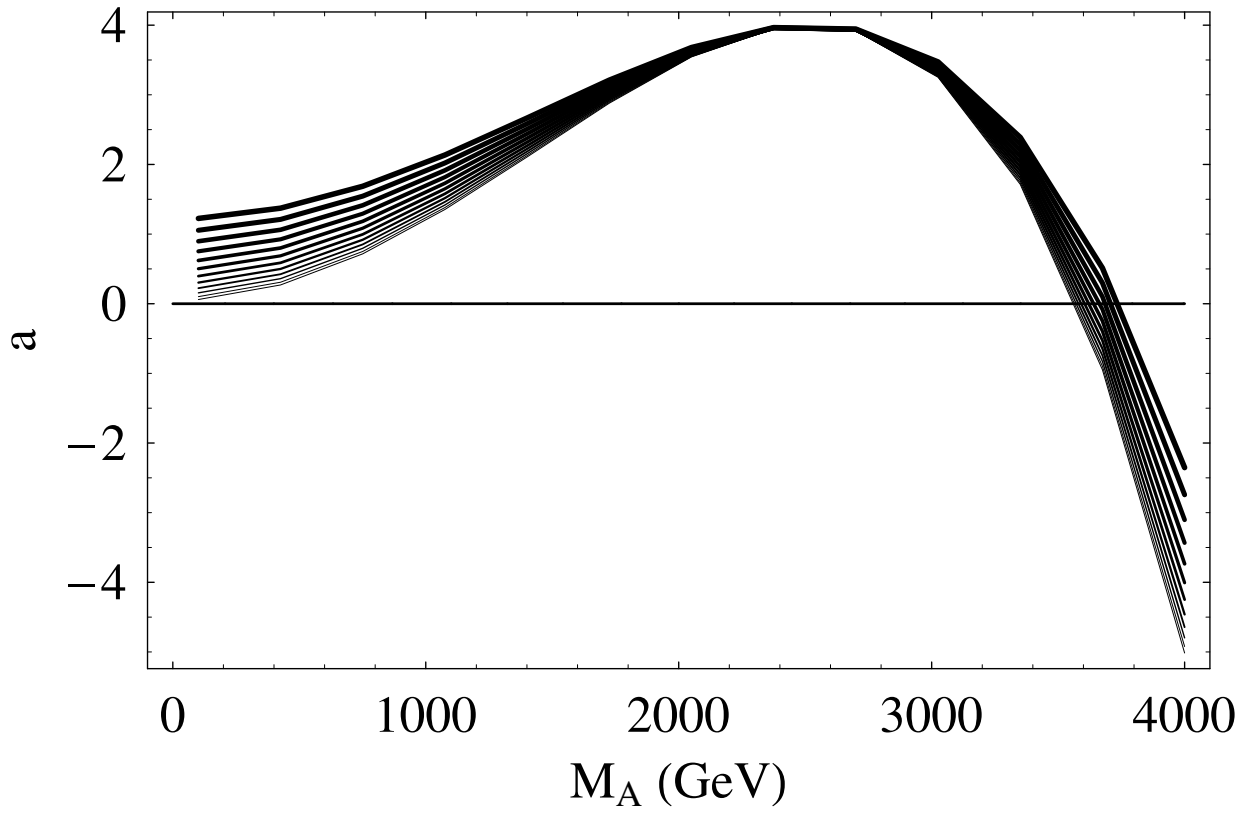
$$g_1, g_2, \tilde{g}, v, r_1, r_2, r_3, m, ... \tag{23}$$

- However, we can constrain the effective theory by imposing Weinbergs 1st Sum Rule and $S \sim 0.1$

$$1 + r_2 - 2r_3 = 0 \ , \quad \hat{S} = f(g_2, \tilde{g}, r_3, ...) \ . \tag{24}$$

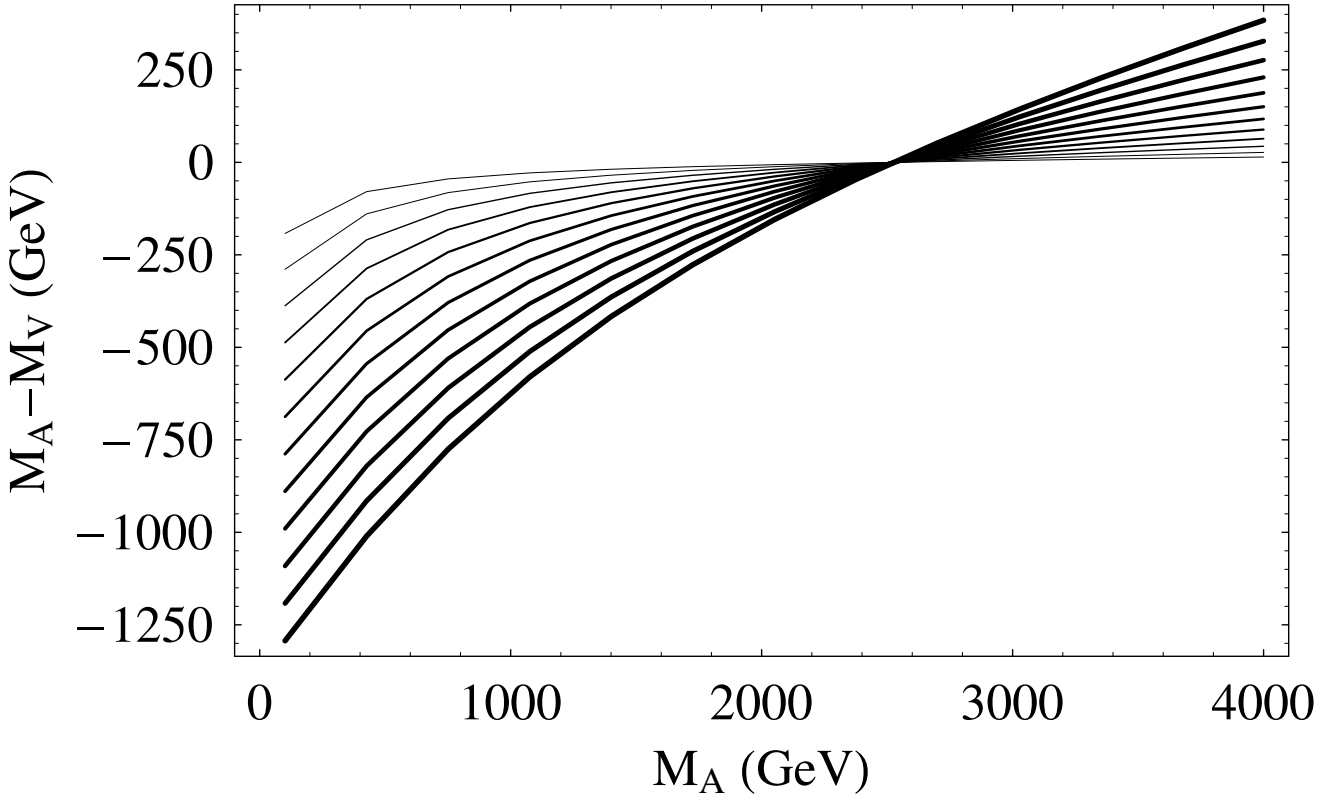
- Inded we can plot the $M_A - M_V$ mass difference and the value of a as functions of $\{\tilde{g}, M_A\}$ only

Modified Sum Rule in MWT



$S = 0.1\ , \qquad \tilde{g} = 1, ..., 8.$

Vector and Axial-Vector Masses in MWT



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Dark Matter Candidates in MWT

- Lightest Neutral Technibaryon

  Gudnason, Kouvaris, Sannino [06]
- 4th Generation Lepton

  Kainulainen, Tuominen, Virkajarvi [06]
- Dressed Techniquarks

  Kouvaris [07]

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3. The effective theory can be linked to the underlying theory thereby constraining it
4. The walking behavior can be modelled using a modified 2nd Weinberg Sum Rule
5. It is possible to have small S and still have relatively light vectors, giving the possibility of interesting LHC phenomenology

Projects

1. Phenomenological analysis of (N)MWT models incl. implementation in Calchep
   Zerwekh [05]; Work in progres w/ A. Belyaev, R. Foadi, F.Sannino

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3. Exploring links with supersymmetry and unparticle physics