

Minimal Walking Technicolor

Francesco Sannino

ILC, Galileo Galilei meeting 2007



Part A

Introducing Technicolor

Precision Data

Walking Dynamics

Part B

Progress in Strong Dynamics

Phase Diagram of Matter in Higher Dimensional Rep.

Alternative Large N limits

First Lattice simulation of a Walking Theory [Catterall-Sannino]

Part C

Minimal Walking Theory

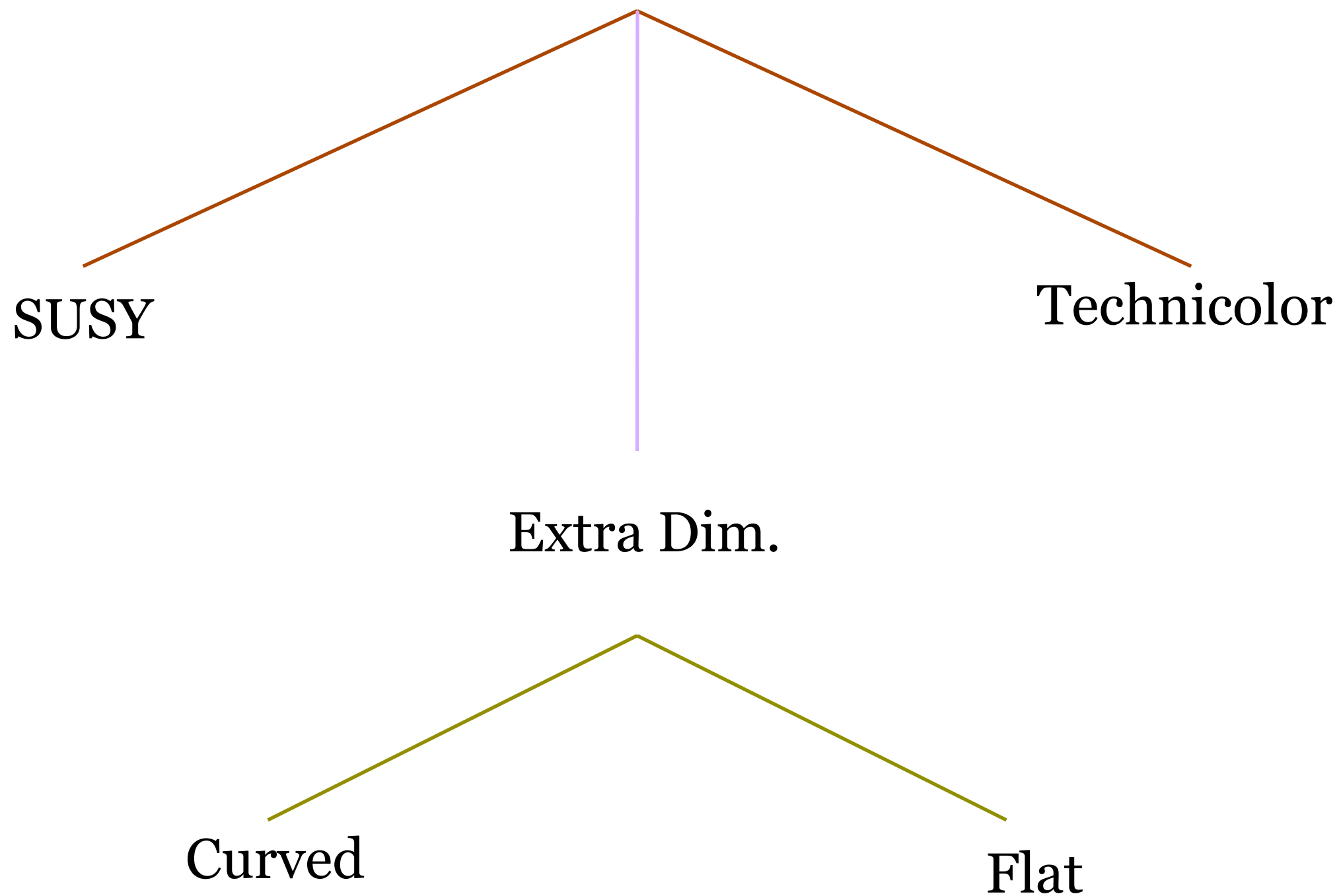
Natural Dark Matter from Technicolor

Playing with Unification

The Lagrangian



Electroweak Symmetry Breaking



Part A

Dynamical EW Breaking

$$L(H) \rightarrow -\frac{1}{4}F^{a\mu\nu}F_{\mu\nu}^a + i\bar{Q}\gamma^\mu D_\mu Q + \dots$$

Dots are partially fixed by Anomalies as well as other principles

$$\dots \rightarrow L(\text{New SM Fermions})$$

Technicolor

New Strong Interactions at ~ 250 GeV
[Weinberg, Susskind]

Natural to use QCD-like dynamics.

$$SU(N)_{TC} \times SU(3)_C \times SU_L(2) \times U_Y(1)$$

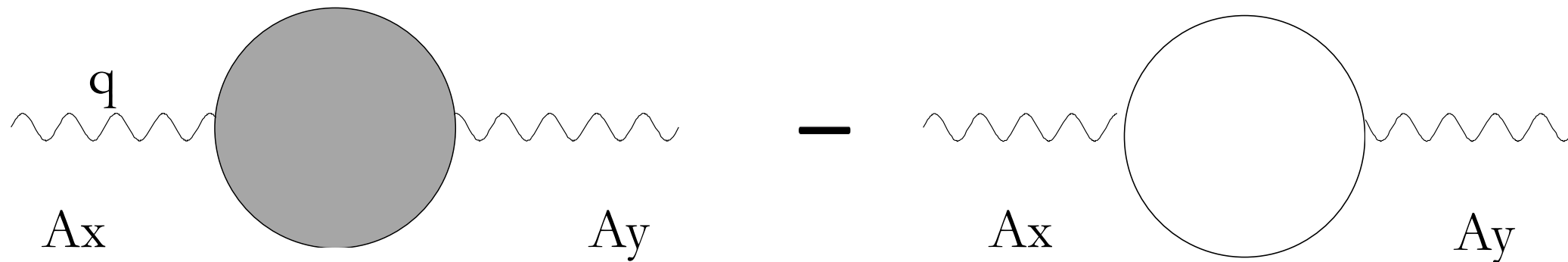
$$\langle Q^f \tilde{Q}_{f'} \rangle = \Lambda_{TC}^3 \qquad \Lambda_{TC} \simeq 250 \text{ GeV}$$

Electroweak Precision Measurements

Kennedy-Lynn, Peskin-Takeuchi, Altarelli-Barbieri, Bertolini- Sirlin, Marciano-Rosner

Ext. SM

SM



$$\Pi_{XY}^{\mu\nu}(q^2) = \Pi_{XY}(q^2)g^{\mu\nu} + \dots$$

S - T

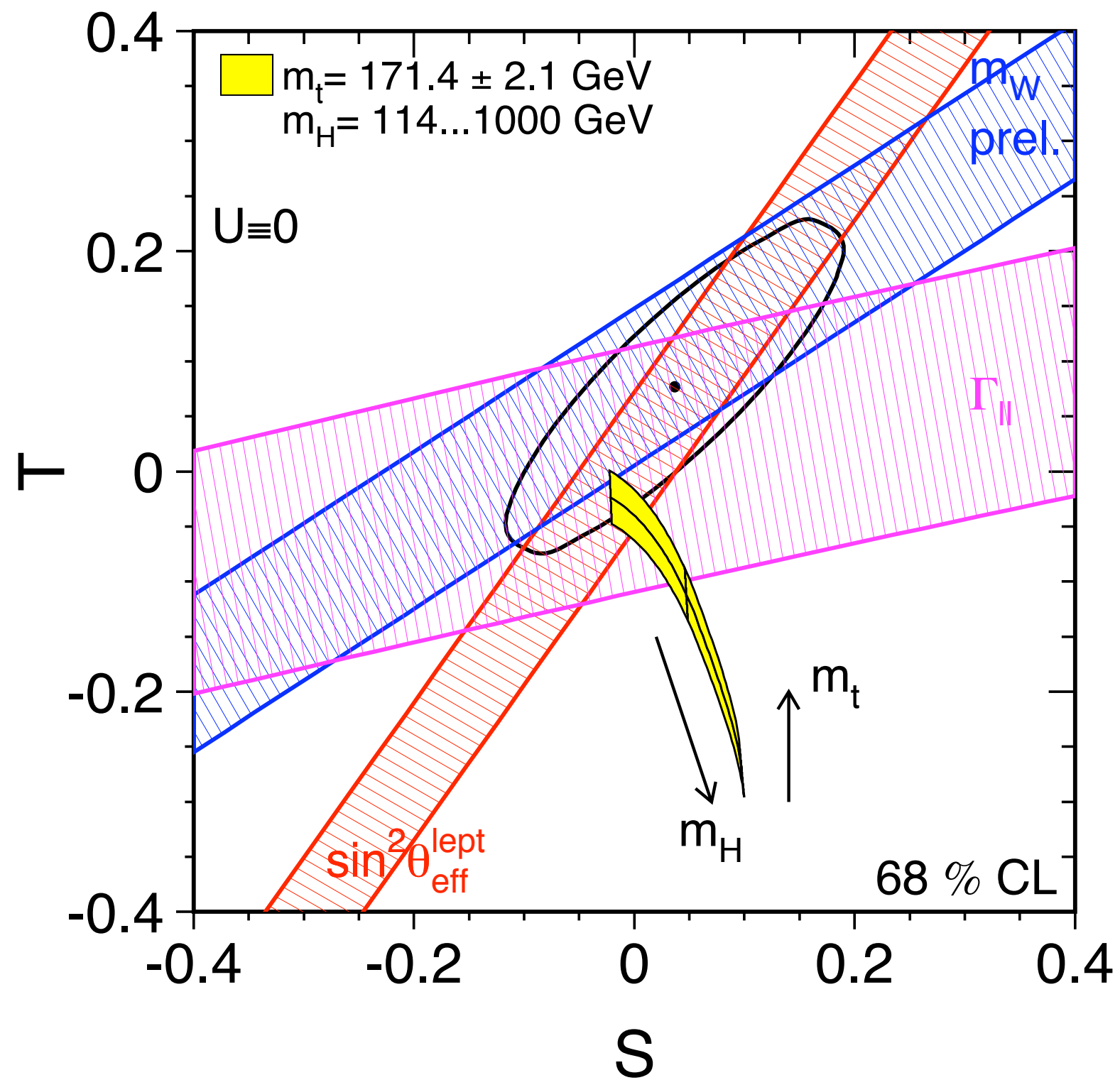
S-measures the left - right type current correlator

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

T-measures deviations from

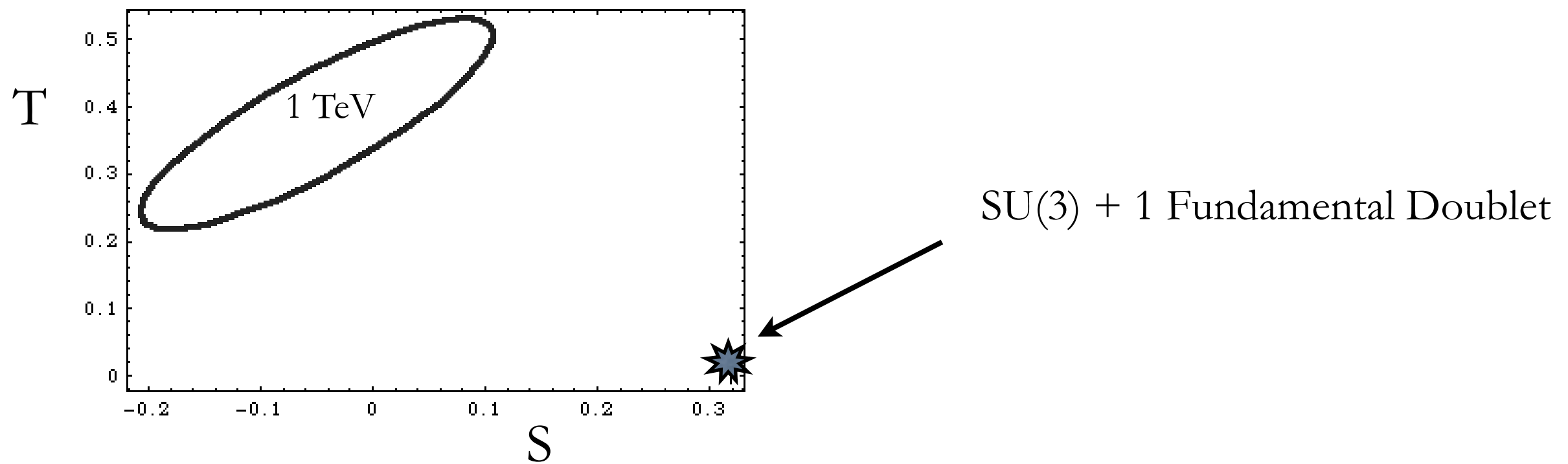
$$m_W^2 = \cos^2 \theta_W m_Z^2$$

$$T = 4\pi \frac{\Pi_{11}(0) - \Pi_{33}(0)}{s_W^2 c_W^2 m_Z^2}$$



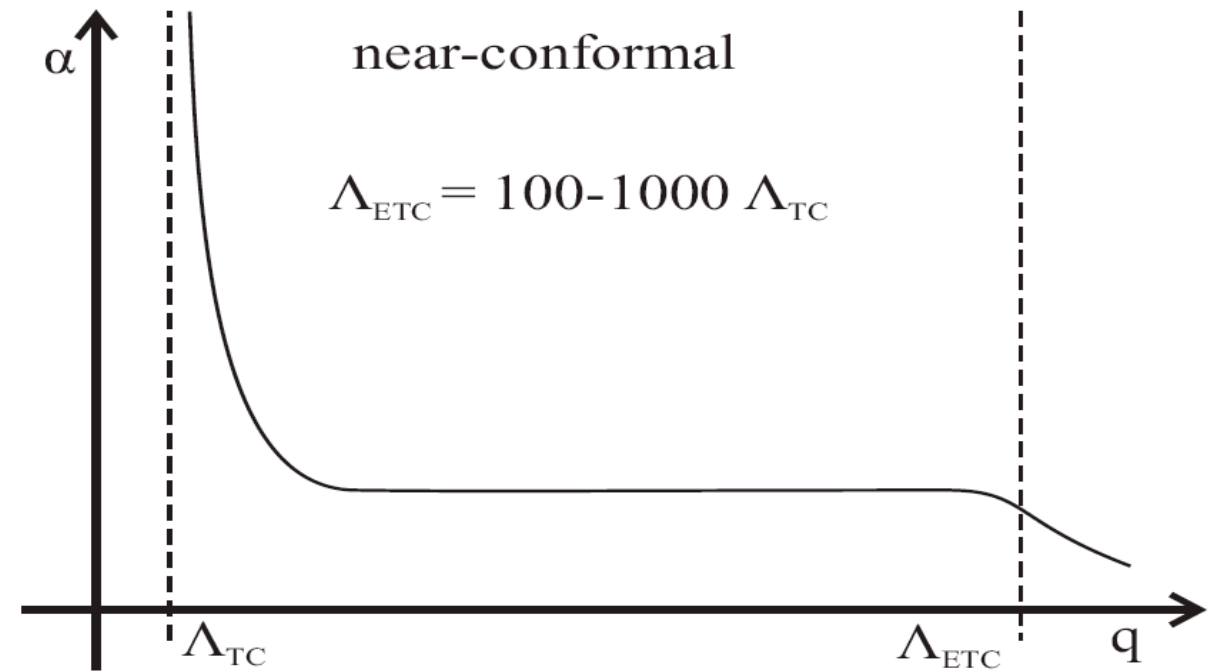
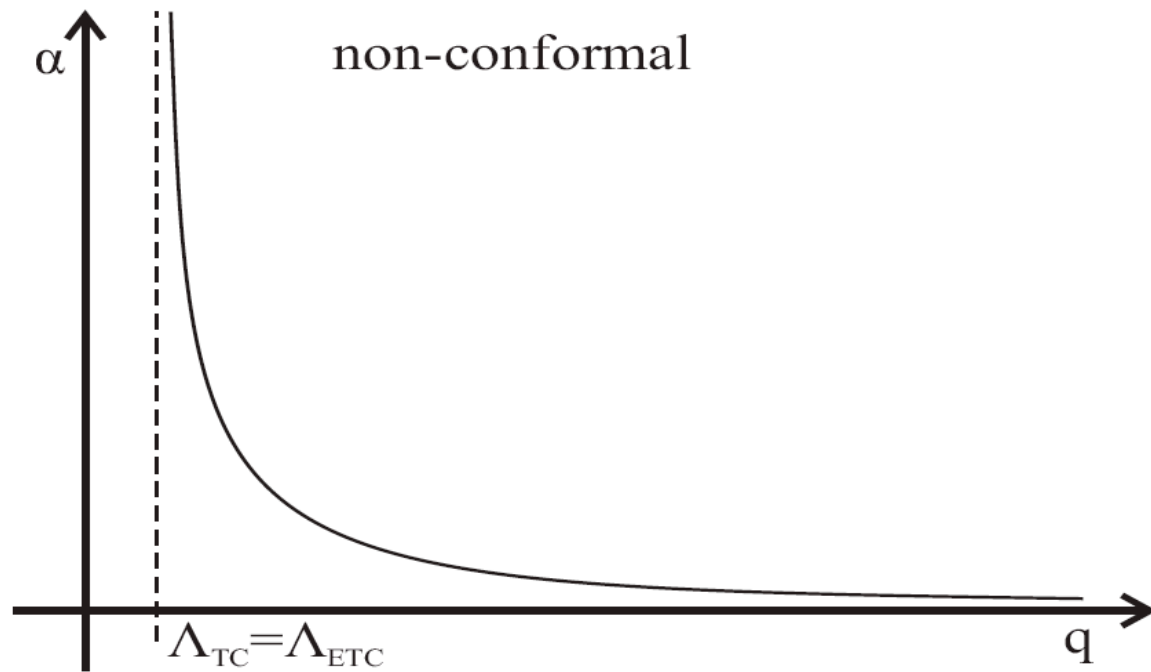
Large & Positive S from QCD-like TC

Peskin and Takeuchi, 90



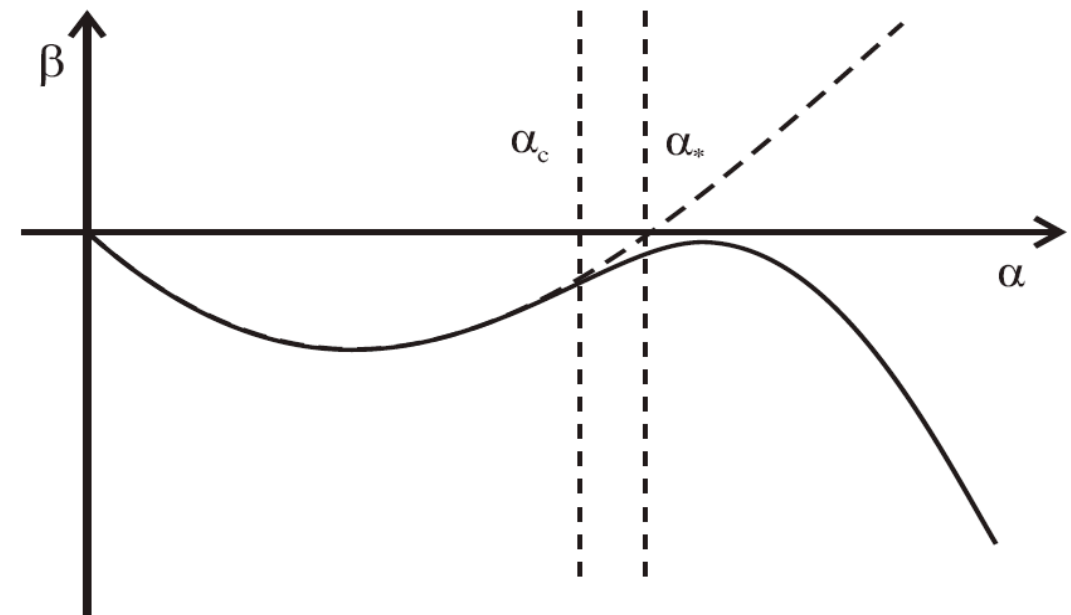
Walking versus Running

Near Conformal Properties



Holdom,
Eichten and Lane,
Appelquist, Miransky, Yamawaki
Cohen and Georgi

Close to the Unparticle World



Part B

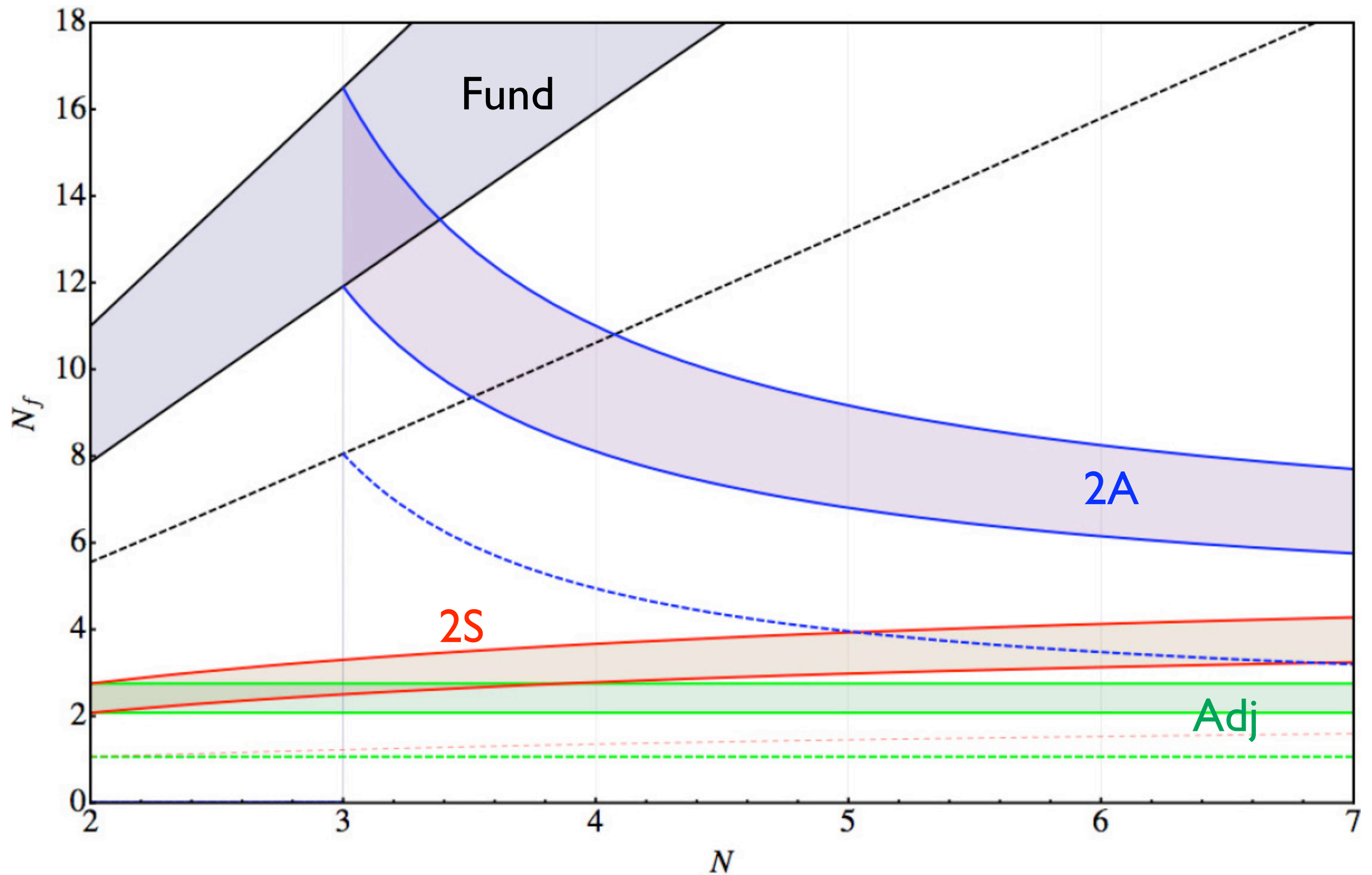


Progress in Strong Interactions

Phase Diagram of Higher Dimensional Representations

New Limits for Strongly Interacting Theories

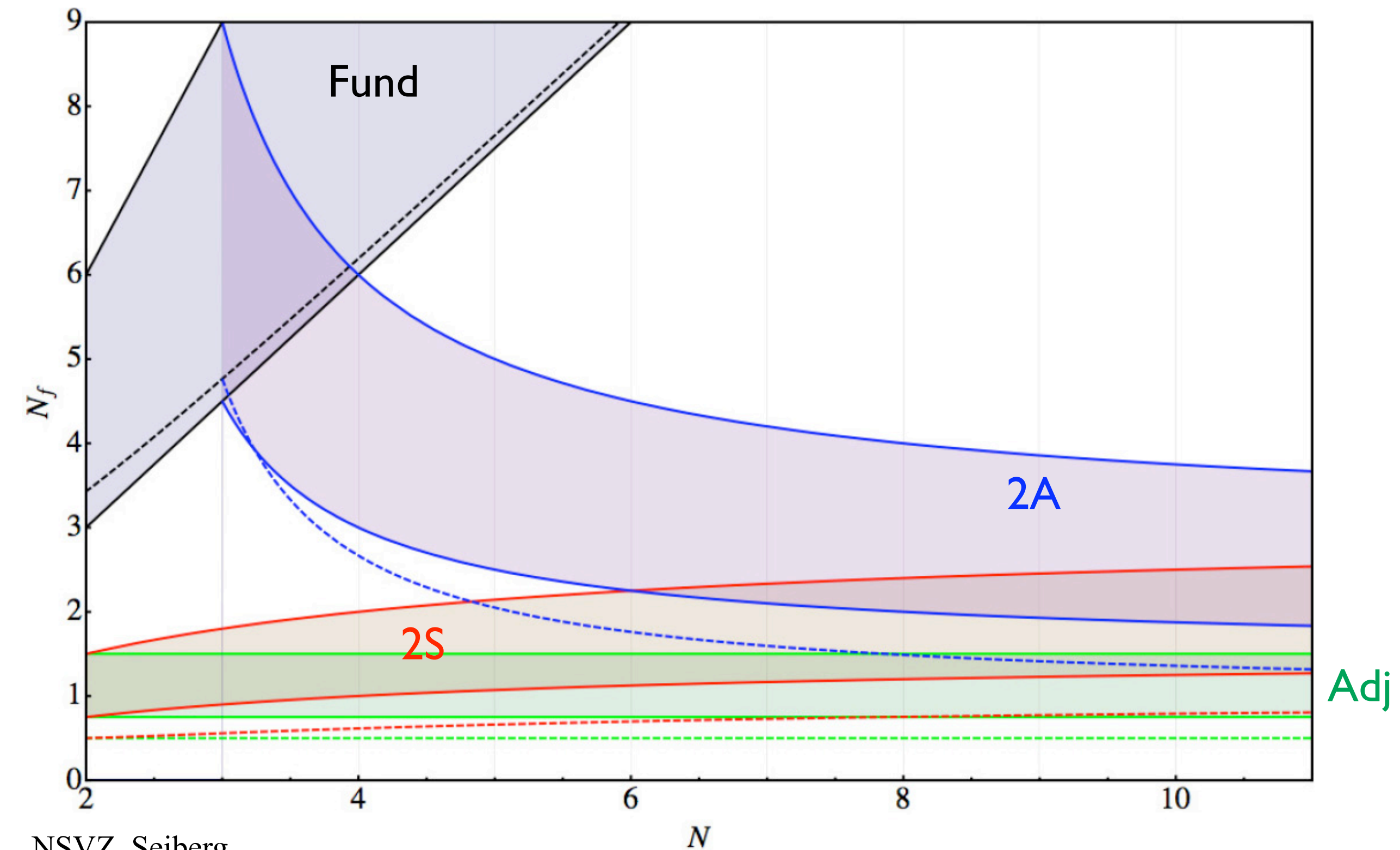
Non-SUSY Phase Diagram for HDRs



Ladder approximation

Dietrich and F.S. 06

SUSY Phase Diagram for HDRs



NSVZ, Seiberg

Intriligator-Seiberg

Ryttov and F.S. 07

A Measure in Theory Space

$$R_{FP} = \frac{A_{\text{Conformal}}}{A_{\text{AF}}}$$

Rep. independent in SUSY

$$R_{FP} = \frac{1}{2}$$

In non-SUSY is rep. independent within the approximations

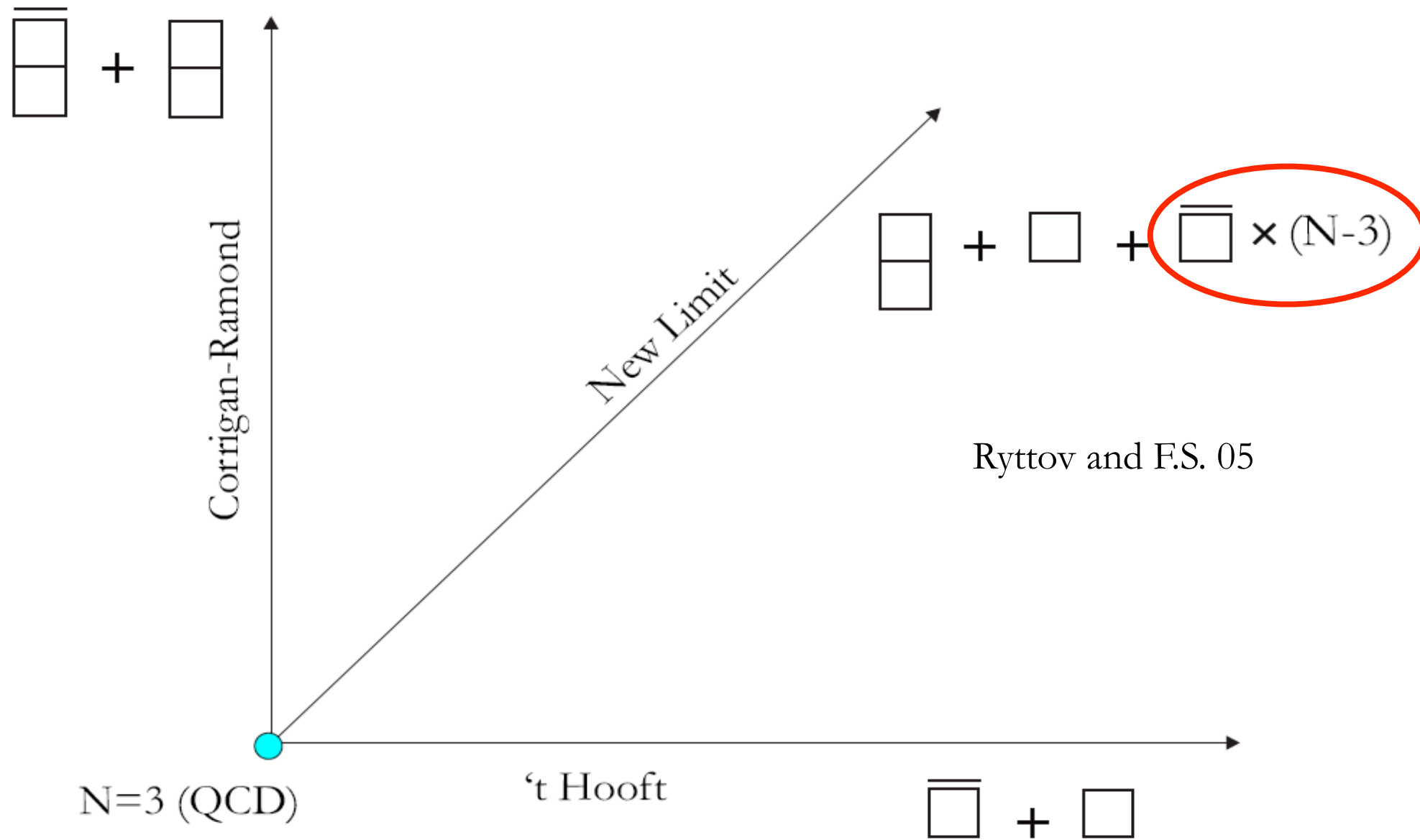
$$R_{FP}[F] = \frac{3}{11} \simeq 0.27 \ , \quad R_{FP}[G] = R_{FP}[A] = R_{FP}[S] = \frac{27}{110} \simeq 0.24$$

Universal Ratio

Information on nonperturbative aspects of HDRs

3 Large N Limits

Armoni-Shifman-Veneziano



F.S. 05, [Temperature]

Frandsen, Kouvaris, F.S. 06, [Density]

F.S. & Schechter 07 [pion-pion scattering]

Kiritsis-Papavassiliou 90

Unsal, 07

Unsal, Yaffe, 06

Kovtun, Unsal, Yaffe 03

Part C

The Minimal Walking Theory

2 Adj. Dirac Flavors of SU(2)

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

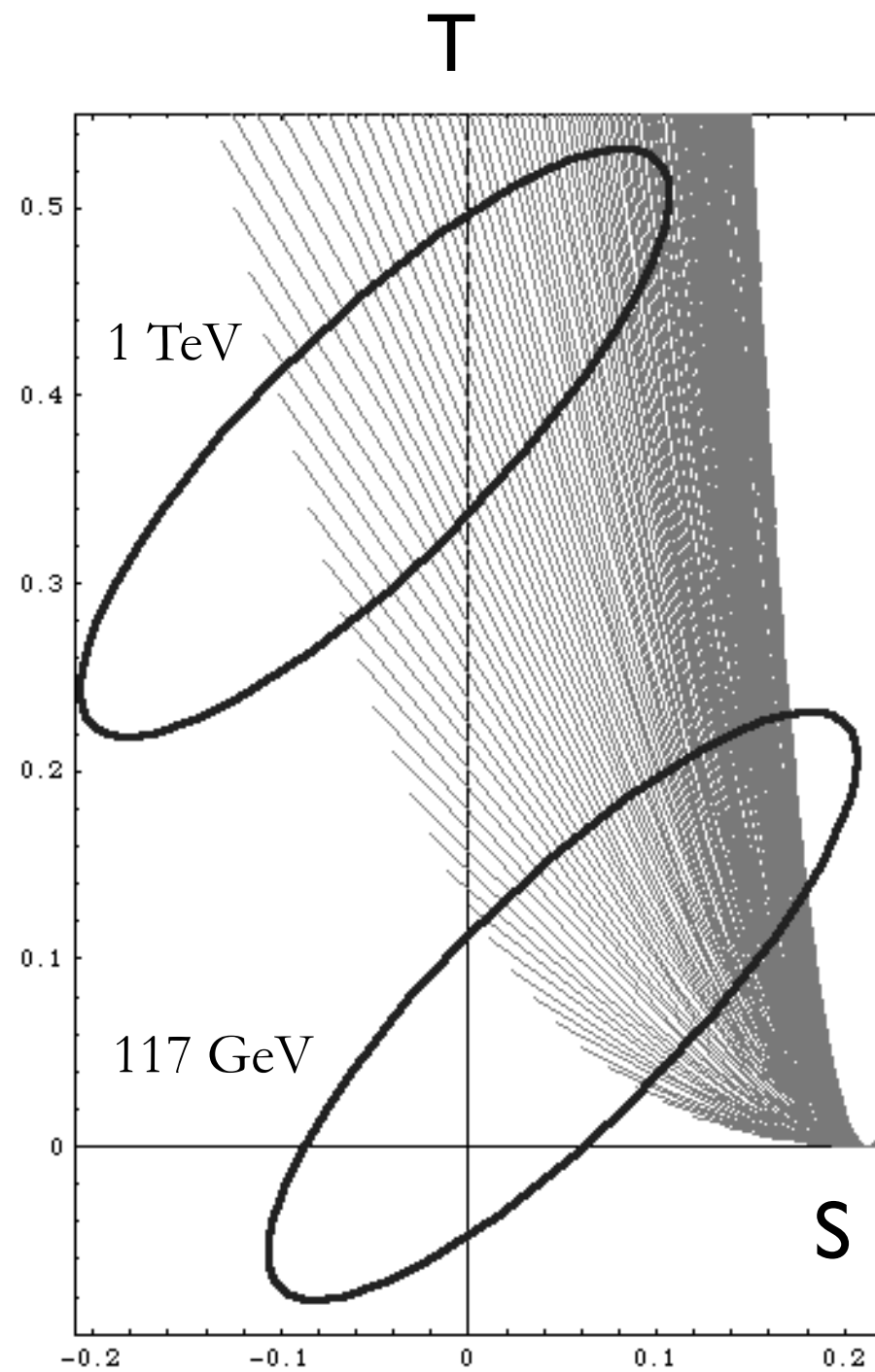
$$Y(Q_L) = \frac{y}{2} \quad Y(U_R, D_R) = \left(\frac{y+1}{2}, \frac{y-1}{2} \right)$$

$$\mathcal{L}_L = \begin{pmatrix} N \\ E \end{pmatrix}_L \quad N_R \quad E_R$$

$$Y(\mathcal{L}_L) = -3\frac{y}{2} \quad Y(N_R, E_R) = \left(\frac{-3y+1}{2}, \frac{-3y-1}{2} \right)$$

$\mathcal{N} = 4$ super Yang-Mills

MWT versus EWPD



LEP EWG Summer 2006

$Y = -3/2$ for Leptons

$100 \text{ GeV} < M_1 < 800 \text{ GeV}$

$100 \text{ GeV} < M_2 < 1000 \text{ GeV}$

$$S_{\text{Leptons}} = \frac{1}{6\pi} \left[1 - 2Y \ln \left(\frac{M_1}{M_2} \right)^2 + \frac{1 + 8Y}{20} \left(\frac{m_Z}{M_1} \right)^2 + \frac{1 - 8Y}{20} \left(\frac{m_Z}{M_2} \right)^2 + O \left(\frac{m_Z^4}{M_i^4} \right) \right]$$

Higgsless versus Higgsfull

Higgsless:

$$\frac{M_H}{M_V} > 1$$

Higgsfull:

$$\frac{M_H}{M_V} \leq 1$$

Spectrum of Hadronic/Technihadronic States

Using 't Hooft Large N and Unitarity in Pion-Pion Scattering in QCD

Vector Meson is a quark-antiquark state:

$\rho(770)$

Broad Sigma of multiquark nature

$f_0(600)$

F.S. & Schechter, 95

Harada, F.S. and Schechter, 03

Caprini, Colangelo, Leutwyler 05

Maiani, Piccinini, Polosa, Riquer 04

F.S. and Schechter, 07

Higgsless: 't Hooft Extension

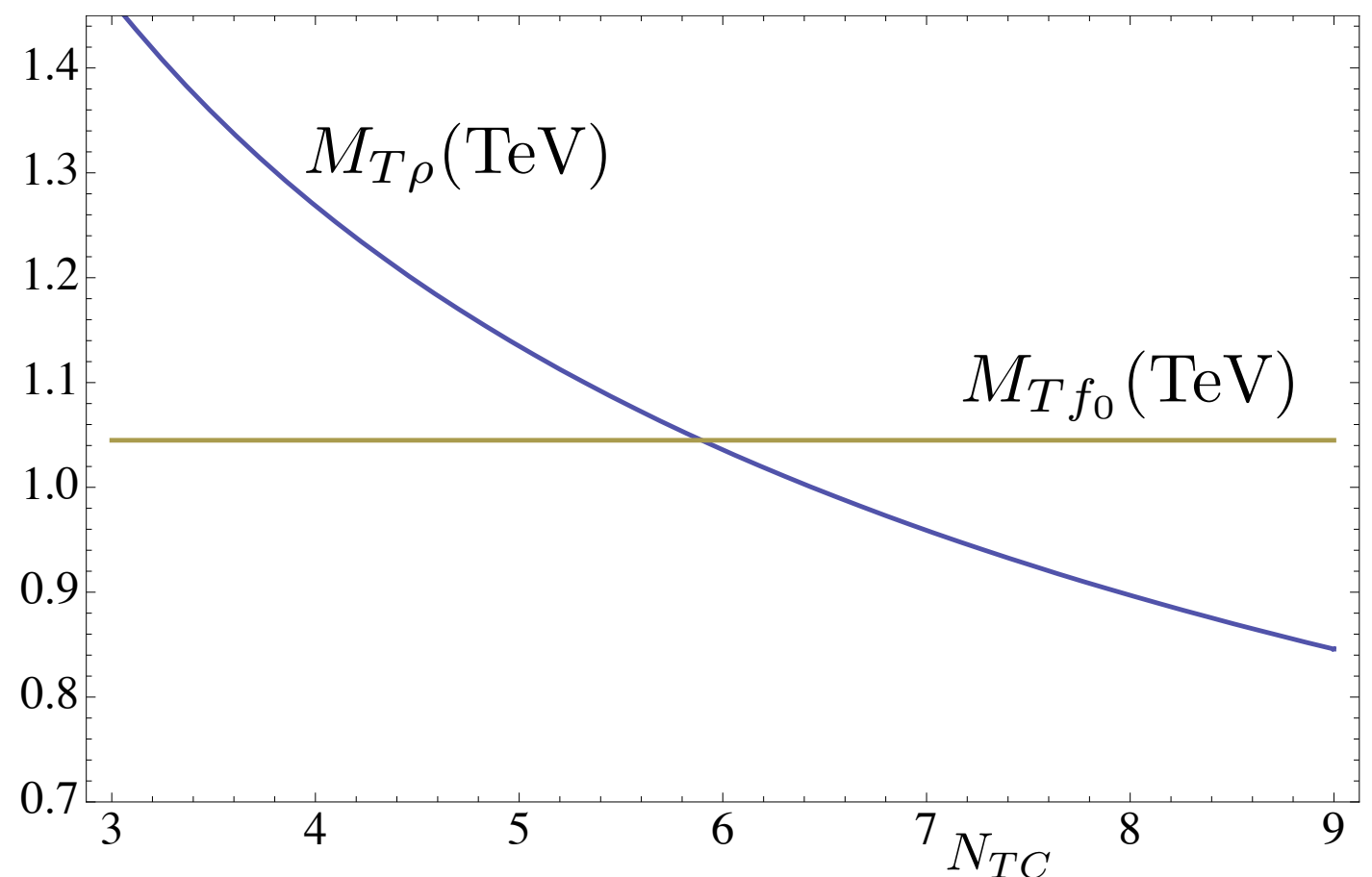
$$M_{T\rho} = \frac{\sqrt{2}v_0}{F_\pi} \frac{\sqrt{3}}{\sqrt{N_D N_{TC}}} m_\rho \quad v_0 \sim 250\text{GeV}$$

$$M_{Tf_0} = \frac{\sqrt{2}v_0}{F_\pi \sqrt{N_D}} \left(\frac{N_{TC}}{\sqrt{3}} \right)^{\frac{p-1}{2}} m_{f_0} \quad p \geq 1$$

F.S. 07

$$N_D = \frac{N_{TF}}{2}$$

$$N_D = 2$$



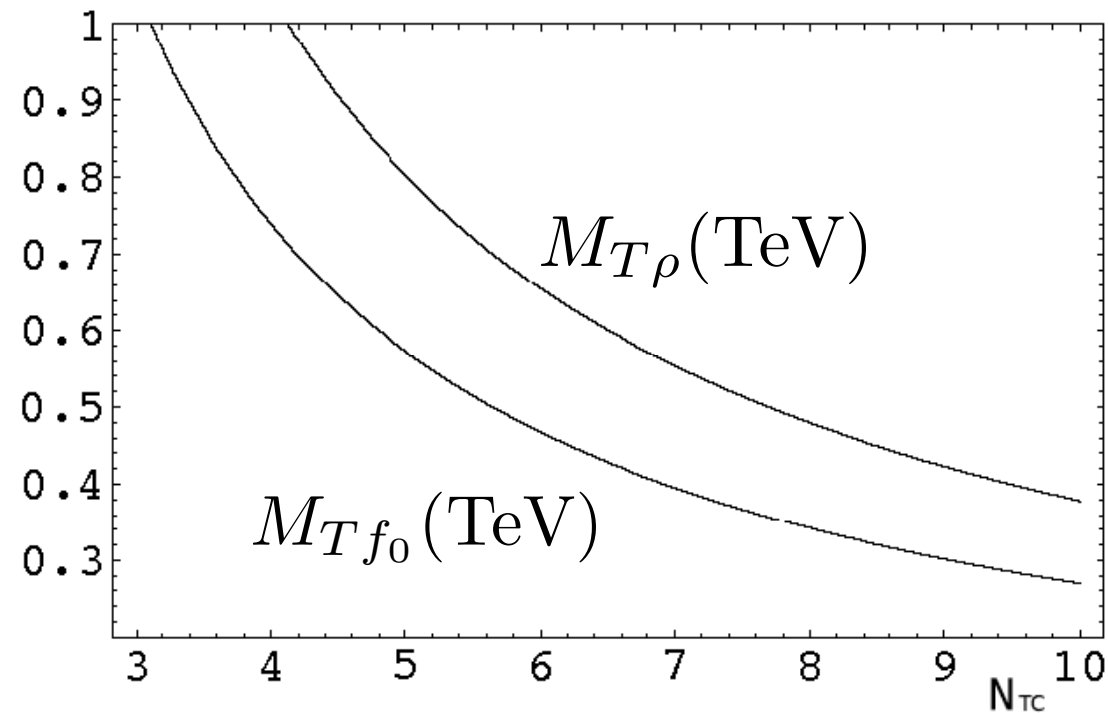
M_H/M_V < 1 in MWT theories

$$M_{T\rho} = \frac{\sqrt{2}v_0}{F_\pi} \frac{\sqrt{3}\sqrt{2}}{\sqrt{N_D N_{TC}(N_{TC} \mp 1)}} m_\rho$$

$$M_{Tf_0} = \frac{\sqrt{2}v_0}{F_\pi} \frac{\sqrt{3}\sqrt{2}}{\sqrt{N_D N_{TC}(N_{TC} \mp 1)}} m_{f_0}$$

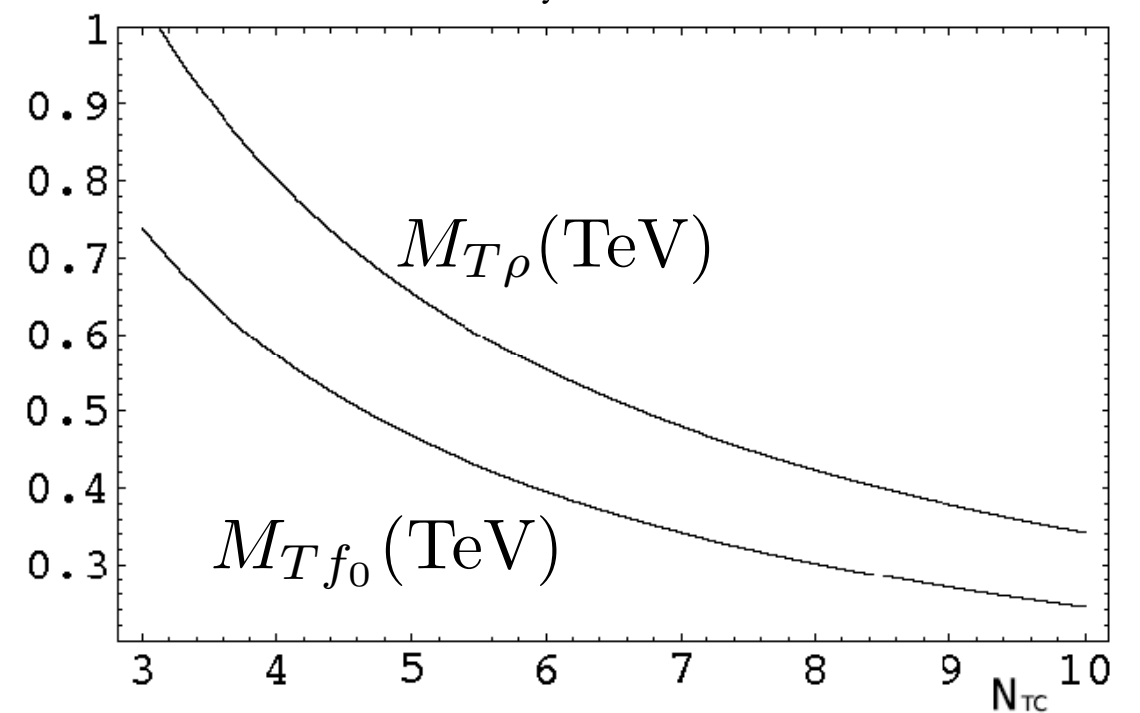
F.S. 07

Antisymmetric



$N_D = 2$

Symmetric



Identified Many EW Viable Walking Models

Minimal Walking Technicolor (MWT)

Higher Dimensional Representations

Beyond Minimal Walking Technicolor

Partially EW Gauged Technicolor

Split Technicolor

Additional Fermions in SM

F.S. - Tuominen 04

Dietrich - F.S. - Tuominen 05

Dietrich - F.S. 06

Gudnason, Rytto, F.S. 06

Dark Matter

$$\frac{\Omega_{DM}}{\Omega_B} \sim 5$$

DM = Lightest Electrically Neutral Technibaryon

Nussinov, 86

Barr - Chivukula - Farhi 90

Bagnasco - Dine - Thomas 94

Gudnason - Kouvaris - F.S. 06

Naive estimates

$$\frac{m_{TB}}{m_p} \approx \frac{1 \text{ TeV}}{1 \text{ GeV}} = 10^3$$

$$\frac{TB}{B} \propto \exp \left[-\frac{m_{TB}(T^*)}{T^*} \right] \sim 10^{-3} \qquad T^* \sim 200 \text{ GeV}$$

$$\frac{\Omega_{TB}}{\Omega_B} = \frac{TB}{B} \frac{m_{TB}}{m_p} \sim \mathcal{O}(1)$$

Conditions

Universe Electric Neutrality

Chemical Equilibrium

EW Sphaleron Processes, Kuzmin-Rubakov-Shaposhnikov

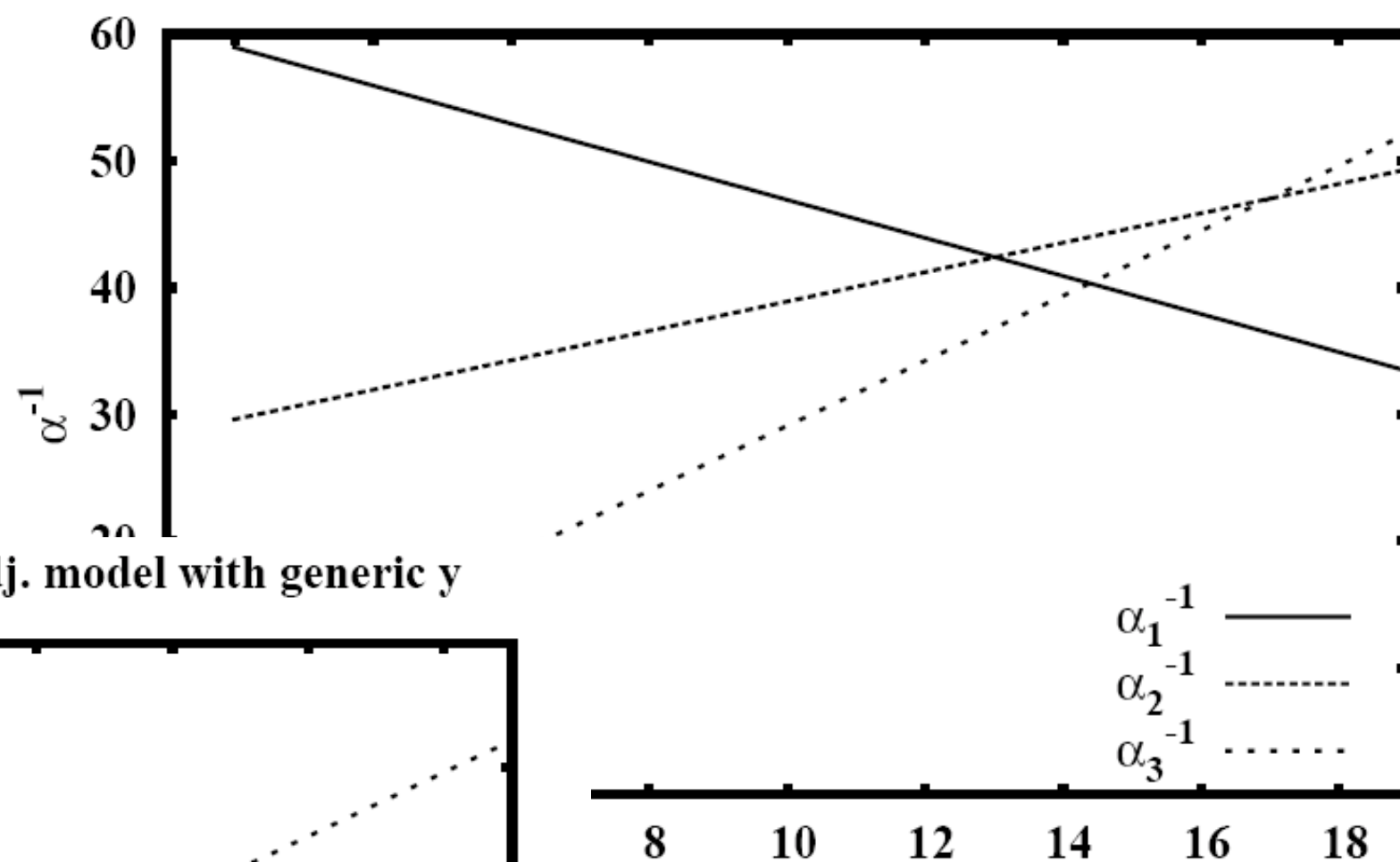
TB - B violated at High Energies & approx. conserved at EW

Playing with Unification

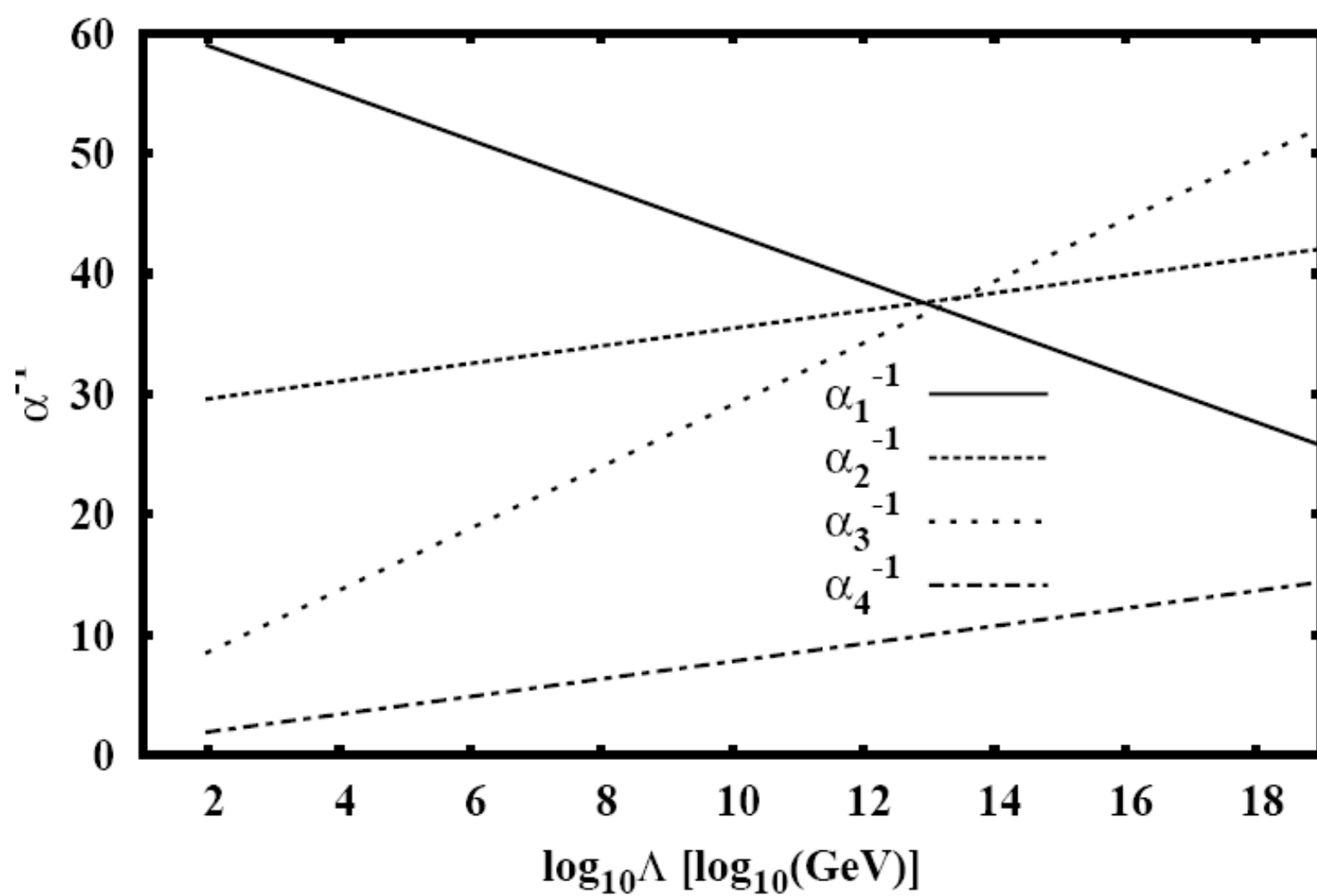
Farhi-Susskind, 79

Gudnason-Ryttov-F.S. 06

Gauge couplings of the SM



Gauge couplings of the SU(2)-Adj. model with generic y

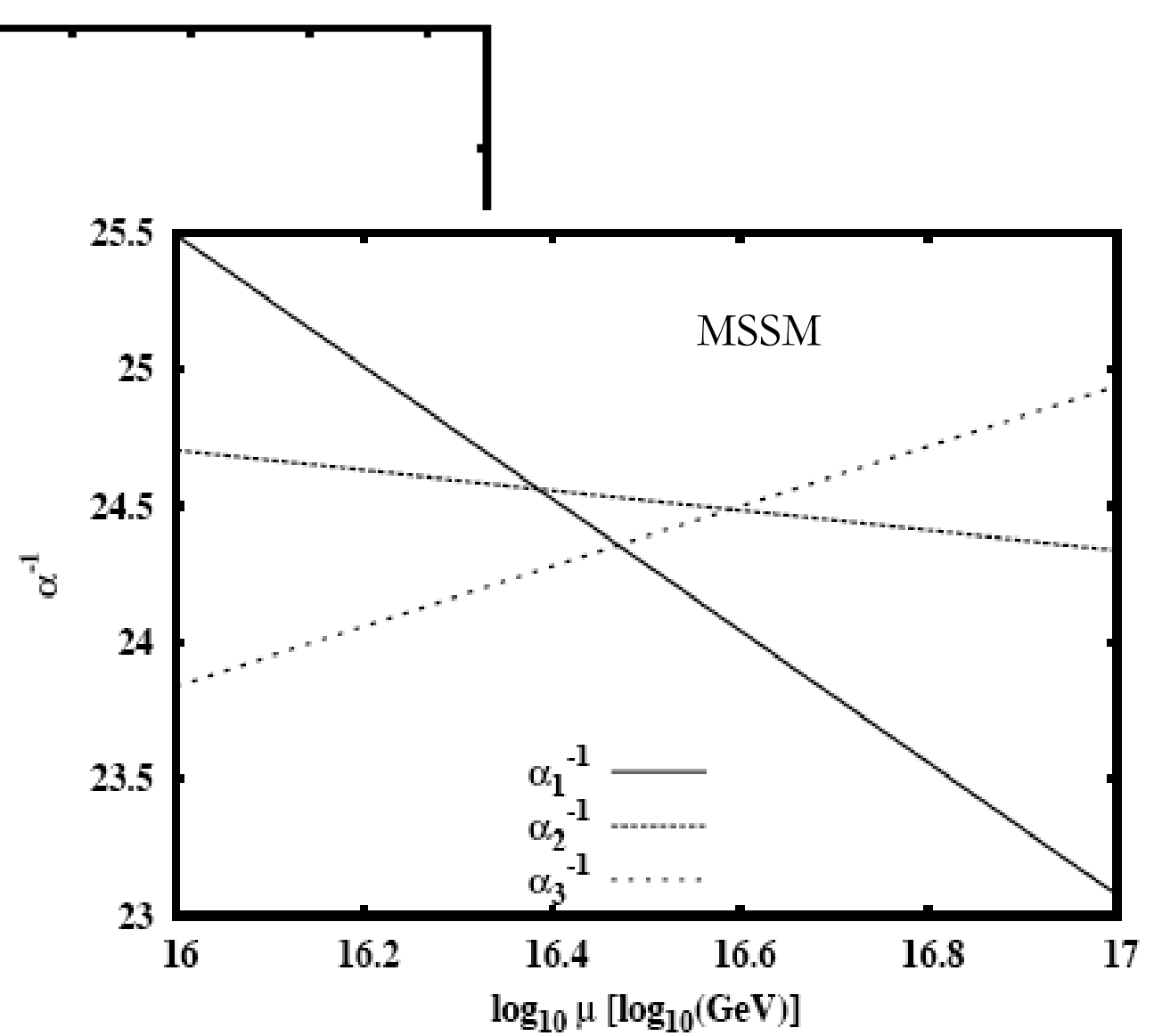
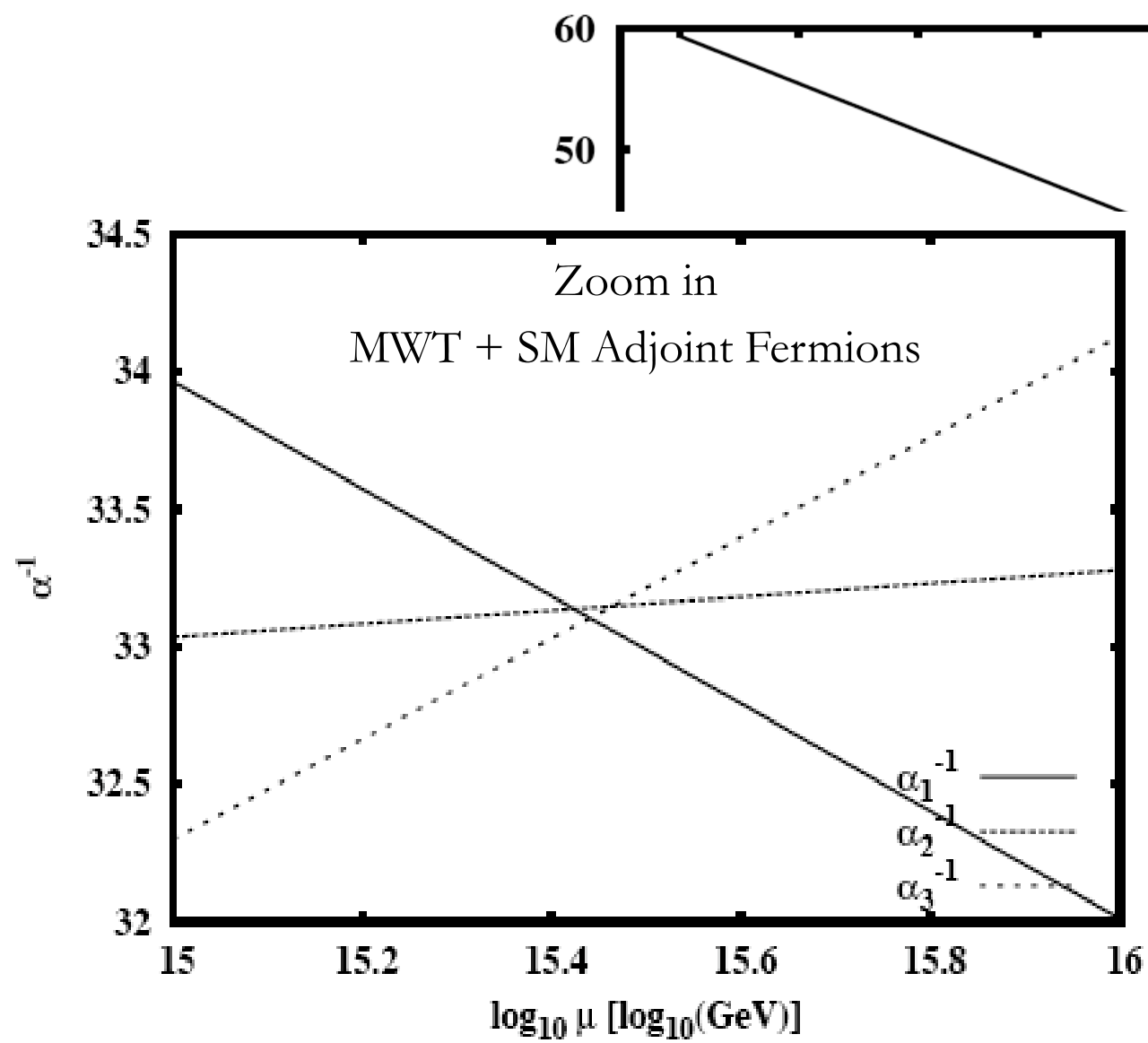


$\log_{10} \Lambda$ [log₁₀(GeV)]

Improving on Unification

Adding New Fermions in the SM

MWT + SM Adjoint Fermions



Comprehensive Effective Technicolor Lagrangian

Vector Mesons

Yukawas

**** Link to MWT via Modified Weinberg Sum Rules ****

Written in a renormalisable form

With imposed constraints from Precision Data

A working technicolor benchmark

$$M_{ij} \sim Q_i^\alpha Q_j^\beta \varepsilon_{\alpha\beta}$$

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

$$A_i^{\mu,j} \sim Q_i^\alpha \sigma_{\alpha\dot{\beta}}^\mu \bar{Q}^{\dot{\beta},j} - \frac{1}{4} \delta_i^j Q_k^\alpha \sigma_{\alpha\dot{\beta}}^\mu \bar{Q}^{\dot{\beta},k}$$

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

$$\begin{aligned}
\mathcal{L}_{\text{Higgs}} = & \frac{1}{2} \text{Tr} [D_\mu M D^\mu M^\dagger] + \frac{m^2}{2} \text{Tr}[M M^\dagger] \\
& - \frac{\lambda}{4} \text{Tr} [M M^\dagger]^2 - \lambda' \text{Tr} [M M^\dagger M M^\dagger] + 2\lambda'' [\text{Det}(M) + \text{Det}(M^\dagger)] \\
& + \frac{m_{\text{ETC}}^2}{\Lambda} \text{Tr} [M B M^\dagger B + M M^\dagger] \ ,
\end{aligned}
\qquad
v^2 = \langle \sigma \rangle^2 = \frac{m^2}{\lambda + \lambda' - \lambda''}$$

$$\begin{aligned}
\mathcal{L}_{\text{fermion}} = & i \, \bar{q}_{\dot{\alpha}}^i \bar{\sigma}^{\mu, \dot{\alpha}\beta} D_\mu q_\beta^i + i \, \bar{l}_{\dot{\alpha}}^i \bar{\sigma}^{\mu, \dot{\alpha}\beta} D_\mu l_\beta^i + i \, \bar{L}_{\dot{\alpha}} \bar{\sigma}^{\mu, \dot{\alpha}\beta} D_\mu L_\beta + i \, \bar{\tilde{Q}}_{\dot{\alpha}} \bar{\sigma}^{\mu, \dot{\alpha}\beta} D_\mu \tilde{Q}_\beta \\
& + x \, \bar{\tilde{Q}}_{\dot{\alpha}} \bar{\sigma}^{\mu, \dot{\alpha}\beta} C_\mu \tilde{Q}_\beta
\end{aligned}$$

$$\begin{aligned}
\mathcal{L}_{\text{Yukawa}} = & - y_u^{ij} q^{iT} (P_U M_{\text{off}}^* P_U) q^j - y_d^{ij} q^{iT} (P_D M_{\text{off}}^* P_D) q^j \\
& - y_\nu^{ij} l^{iT} (P_U M^* P_U) l^j - y_e^{ij} l^{iT} (P_D M^* P_D) l^j \\
& - y_N L^T (P_U M_{\text{off}}^* P_U) L - y_E L^T (P_D M_{\text{off}}^* P_D) L \\
& - y_{\tilde{U}} \tilde{Q}^T (P_U M^* P_U) \tilde{Q} - y_{\tilde{D}} \tilde{Q}^T (P_D M^* P_D) \tilde{Q} + \text{h.c.}
\end{aligned}
\qquad
\begin{aligned}
P_U &= \begin{pmatrix} 1 & 0 \\ 0 & \frac{1+\tau^3}{2} \end{pmatrix} \\
P_D &= \begin{pmatrix} 1 & 0 \\ 0 & \frac{1-\tau^3}{2} \end{pmatrix}
\end{aligned}$$

$$\mathcal{L}_{\text{kinetic}} = -\frac{1}{2}\text{Tr}\left[\widetilde{W}_{\mu\nu}\widetilde{W}^{\mu\nu}\right] - \frac{1}{4}B_{\mu\nu}B^{\mu\nu} - \frac{1}{2}\text{Tr}\left[F_{\mu\nu}F^{\mu\nu}\right] + m_A^2 \text{Tr}\left[C_\mu C^\mu\right]$$

$$F_{\mu\nu} = \partial_\mu A_\nu - \partial_\nu A_\mu - i\tilde{g}[A_\mu, A_\nu]$$

$$C_\mu \equiv A_\mu - \frac{g}{\tilde{g}} G_\mu(y) \qquad G_\mu = \begin{pmatrix} W_\mu & 0 \\ 0 & -\frac{g'}{g} B_\mu^T \end{pmatrix} + \frac{y}{2} \frac{g'}{g} B_\mu \begin{pmatrix} 1 & 0 \\ 0 & -1 \end{pmatrix}$$

$$\begin{aligned} \mathcal{L}_{\text{M-C}} = & \tilde{g}^2 r_1 \text{Tr} [C_\mu C^\mu M M^\dagger] + \tilde{g}^2 r_2 \text{Tr} [C_\mu M C^{\mu T} M^\dagger] \\ & + i \tilde{g} r_3 \text{Tr} [C_\mu (M (D^\mu M)^\dagger - (D^\mu M) M^\dagger)] + \tilde{g}^2 s \text{Tr} [C_\mu C^\mu] \text{Tr} [M M^\dagger] \end{aligned}$$

MWT does not reduce to a BESS model

Casalbuoni, De Curtis, Dominici, Gatto 85 BESS models

Summary

- Introduced different types of viable technicolor theories
- Phase diagram of Higher Dimensional Representations
- Presented Minimal Walking Technicolor
- First walking evidences on the lattice, Catterall - F.S. 0705.1664 [hep-lat]
- Dark Matter as a technibaryon
- Unification