Minimal Walking Technicolor

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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

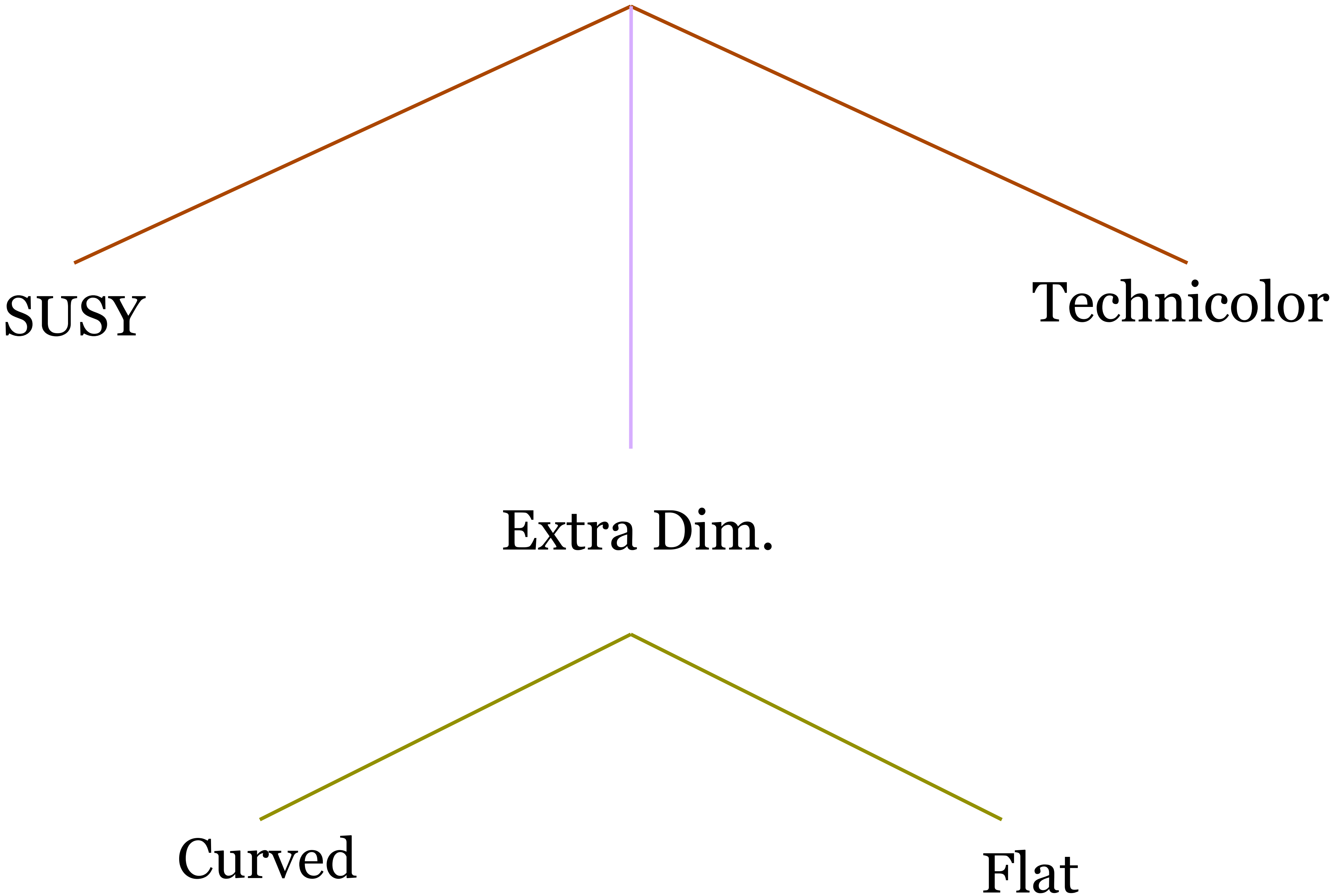
Minimal Walking Theory

Natural Dark Matter from Technicolor

Playing with Unification

The Lagrangian

Electroweak Symmetry Breaking



Part A

Dynamical EW Breaking

$$L(H) \to -\frac{1}{4} F^{a\mu\nu} F^{a}_{\mu\nu} + i\bar{Q}\gamma^{\mu} D_{\mu} Q + \cdots$$

Dots are partially fixed by Anomalies as well as other principles

$$\ldots \quad \to \quad L(\text{New SM Fermions})$$

Technicolor

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

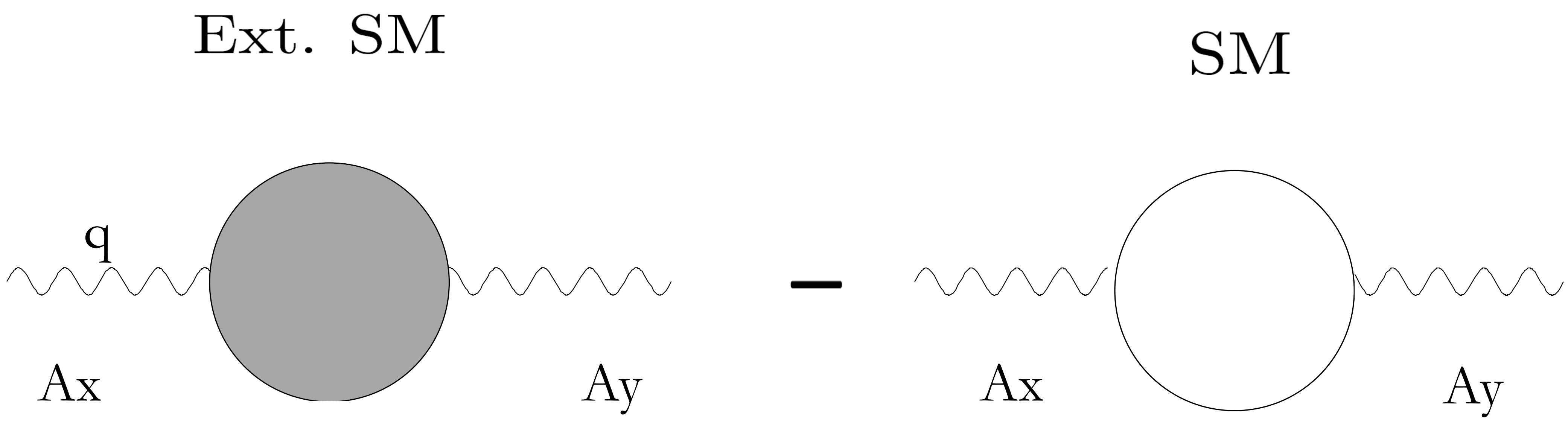
Natural to use QCD-like dynamics.

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

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

Electroweak Precision Measurements

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



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

S - T

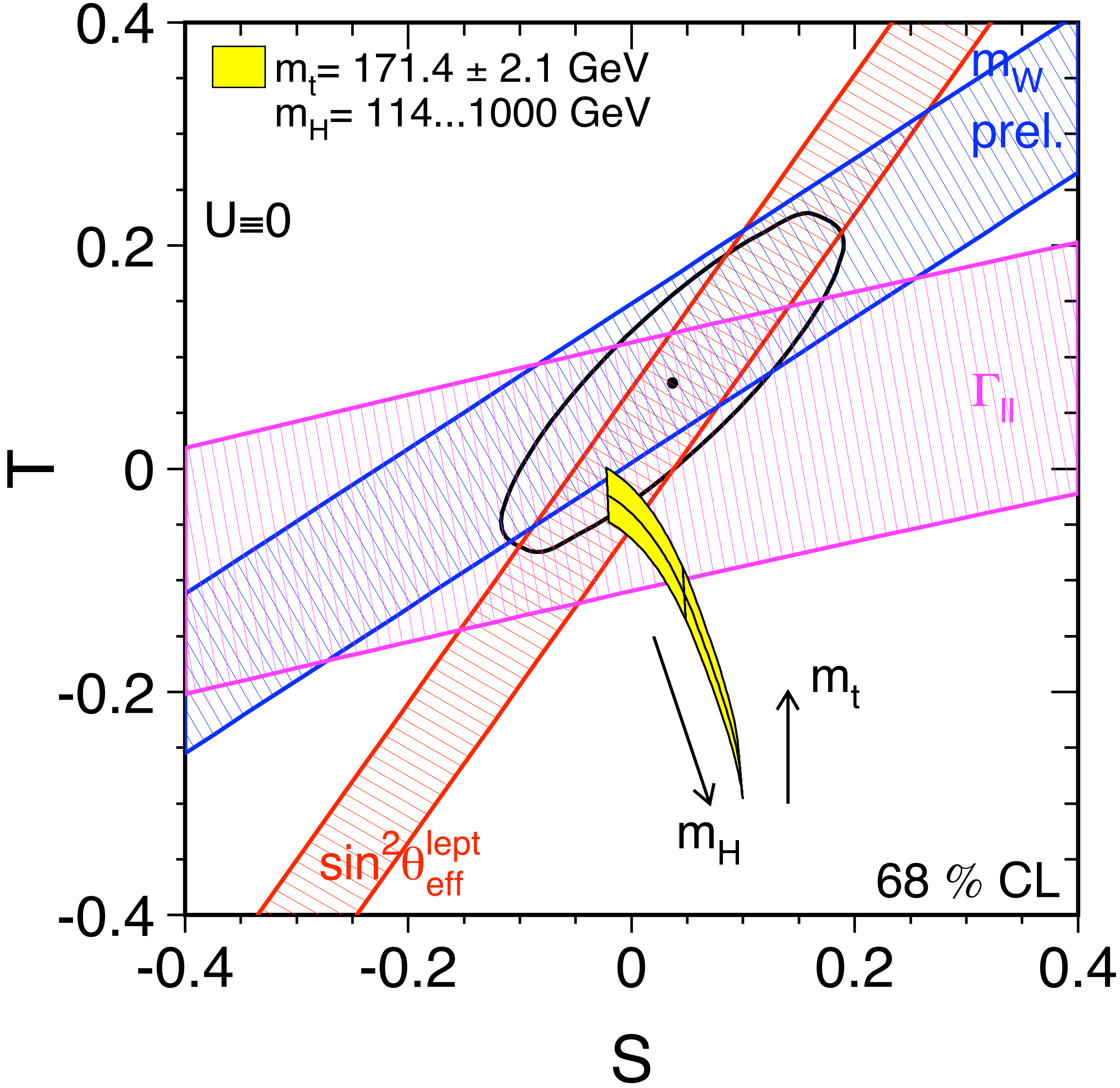
S-measures the left - right type current correlator

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

T-measures deviations from

$$m_{\mathrm{W}}^2 = \cos^2\theta_{\mathrm{W}}\, m_{\mathrm{Z}}^2$$

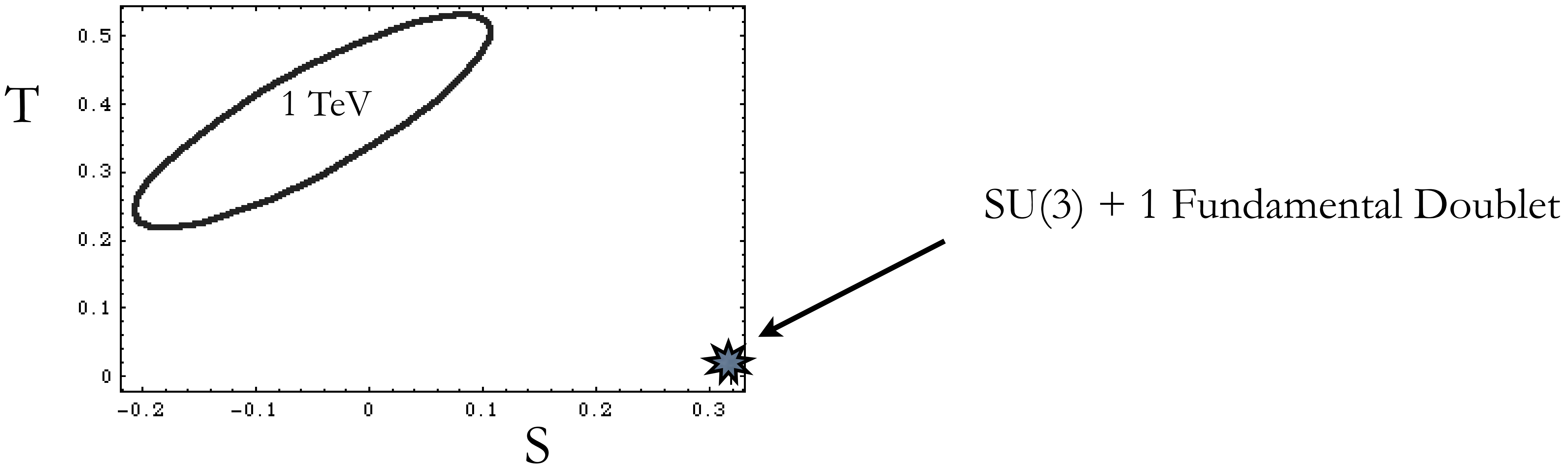
$$T = 4\pi \frac{\Pi_{11}(0) - \Pi_{33}(0)}{s_W^2 c_W^2 m_Z^2}$$



LEP EWG Summer 2006

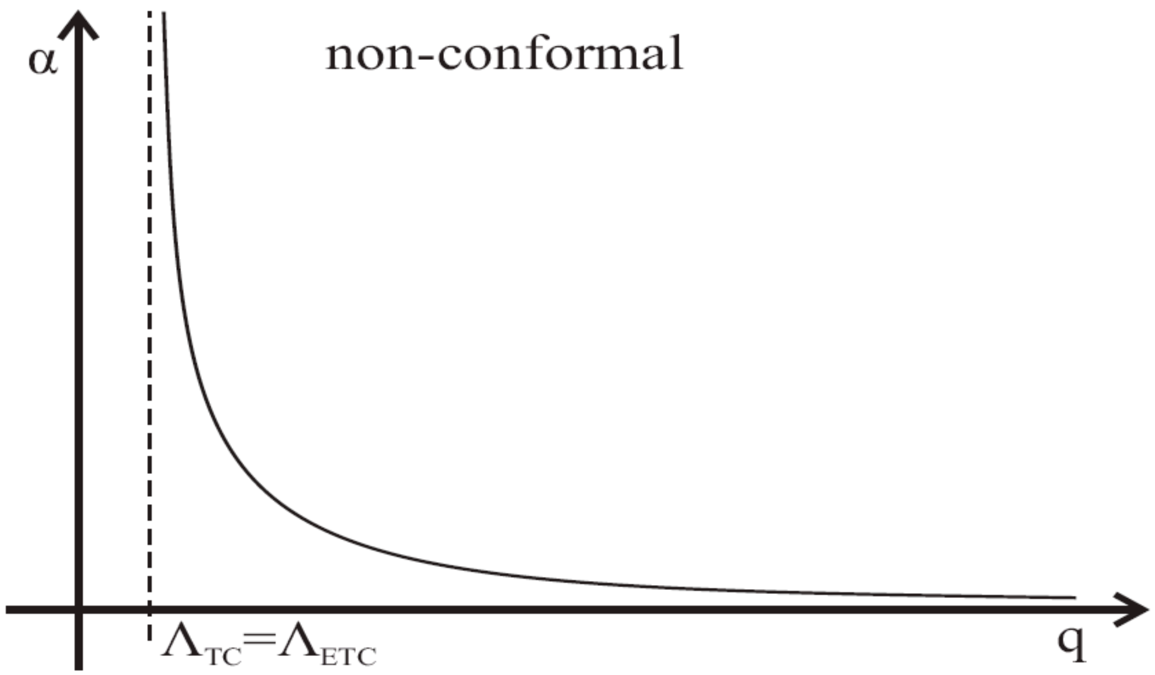
Large & Positive S from QCD-like TC

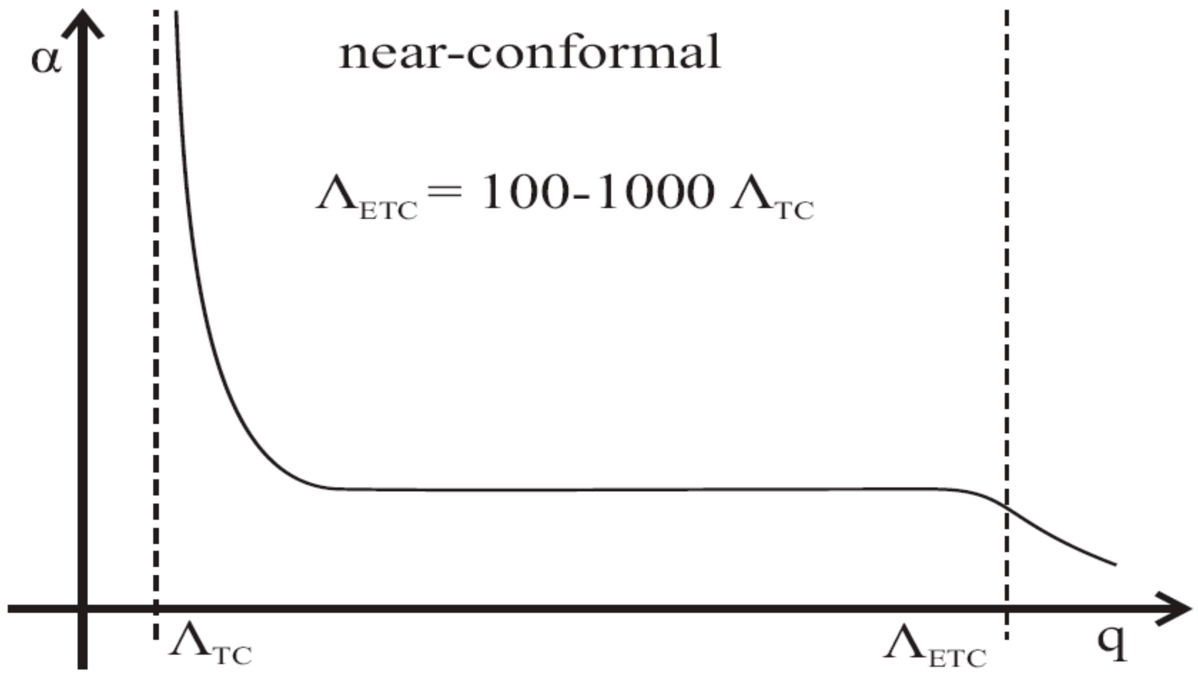
Peskin and Takeuchi, 90



Walking versus Running

Near Conformal Properties



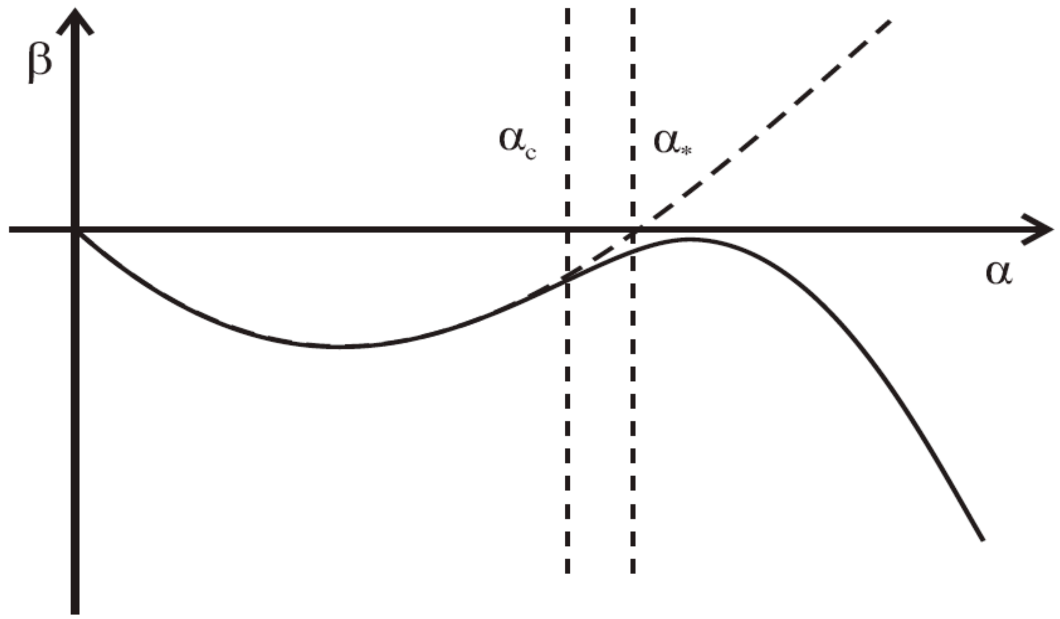


Holdom,

Eicthen and Lane,

Appelquist,Miransky, Yamawaki

Cohen and Georgi



Close to the Unparticle World

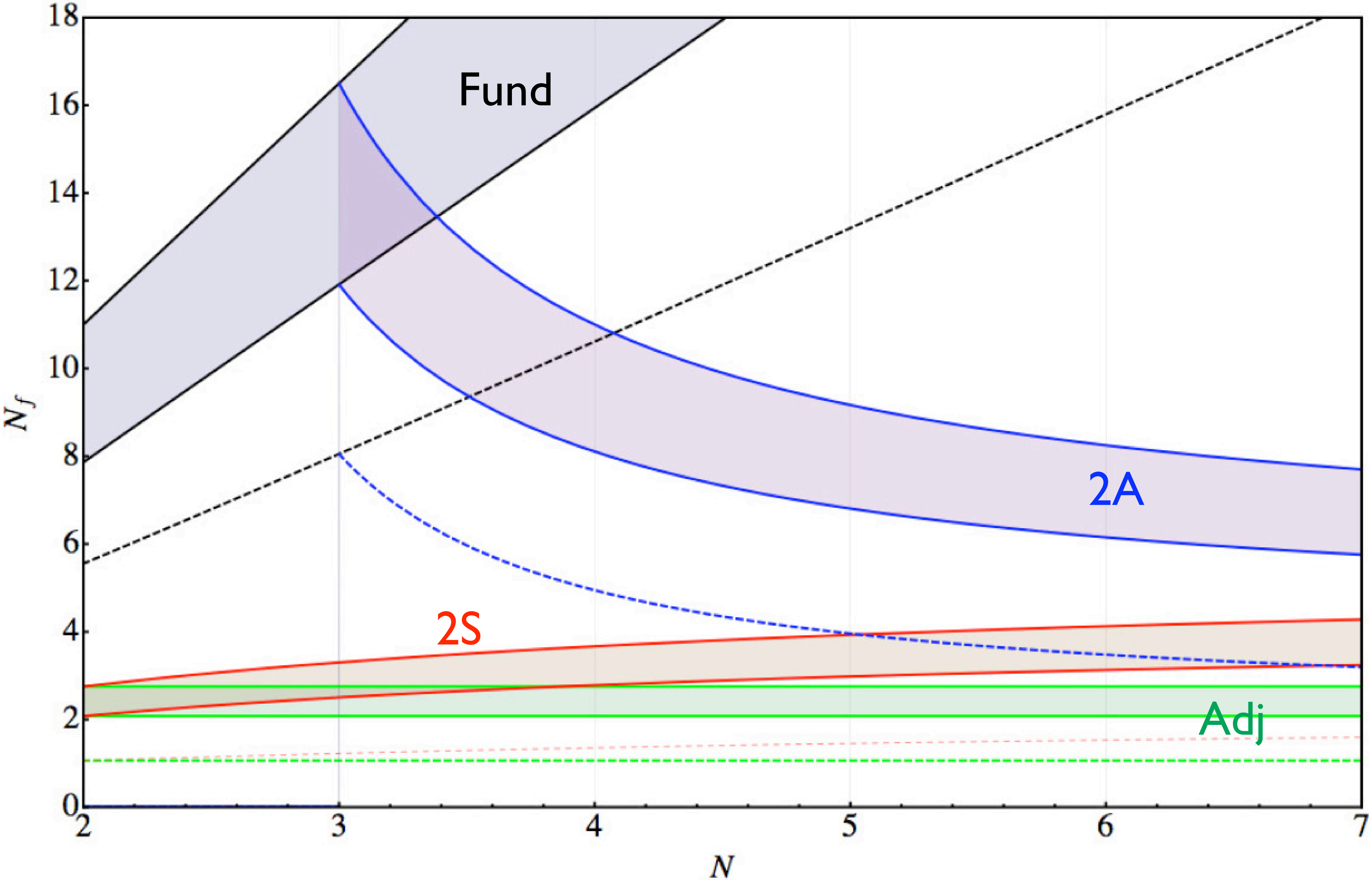
Part B

Progress in Strong Interactions

Phase Diagram of Higher Dimensional Representations

New Limits for Strongly Interacting Theories

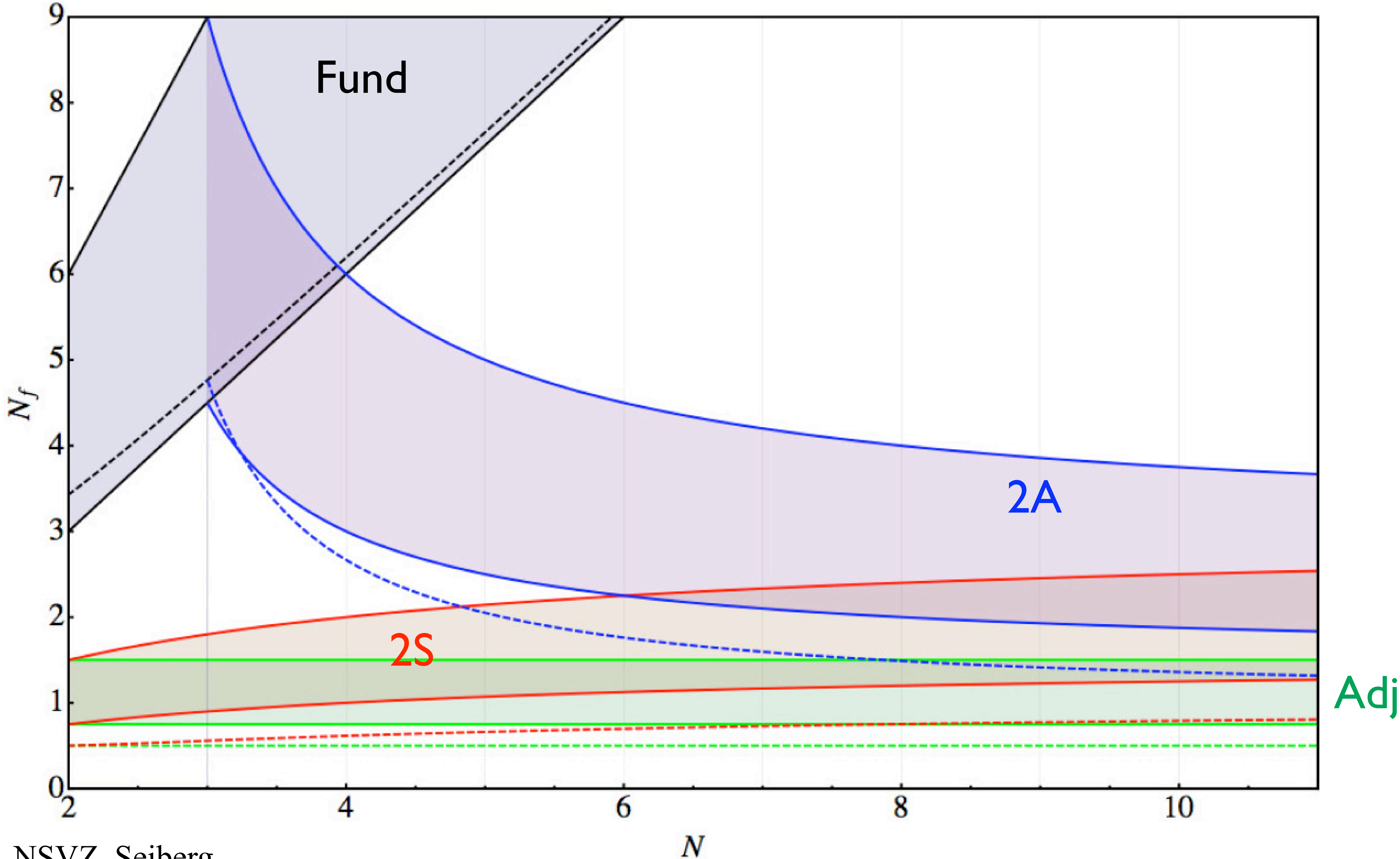
Non-SUSY Phase Diagram for HDRs



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

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

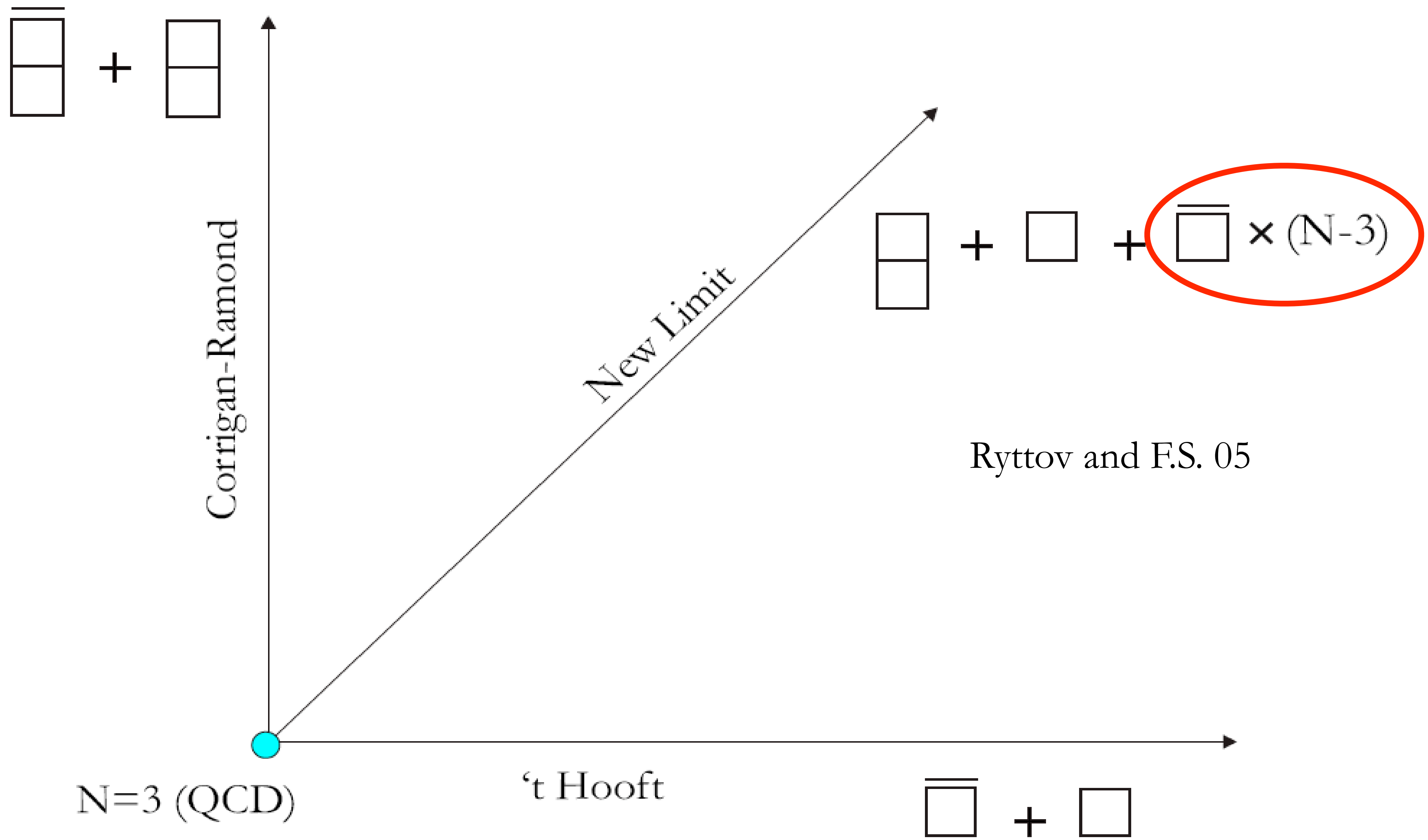
Universal Ratio

Ryttov and F.S. 07

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)

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

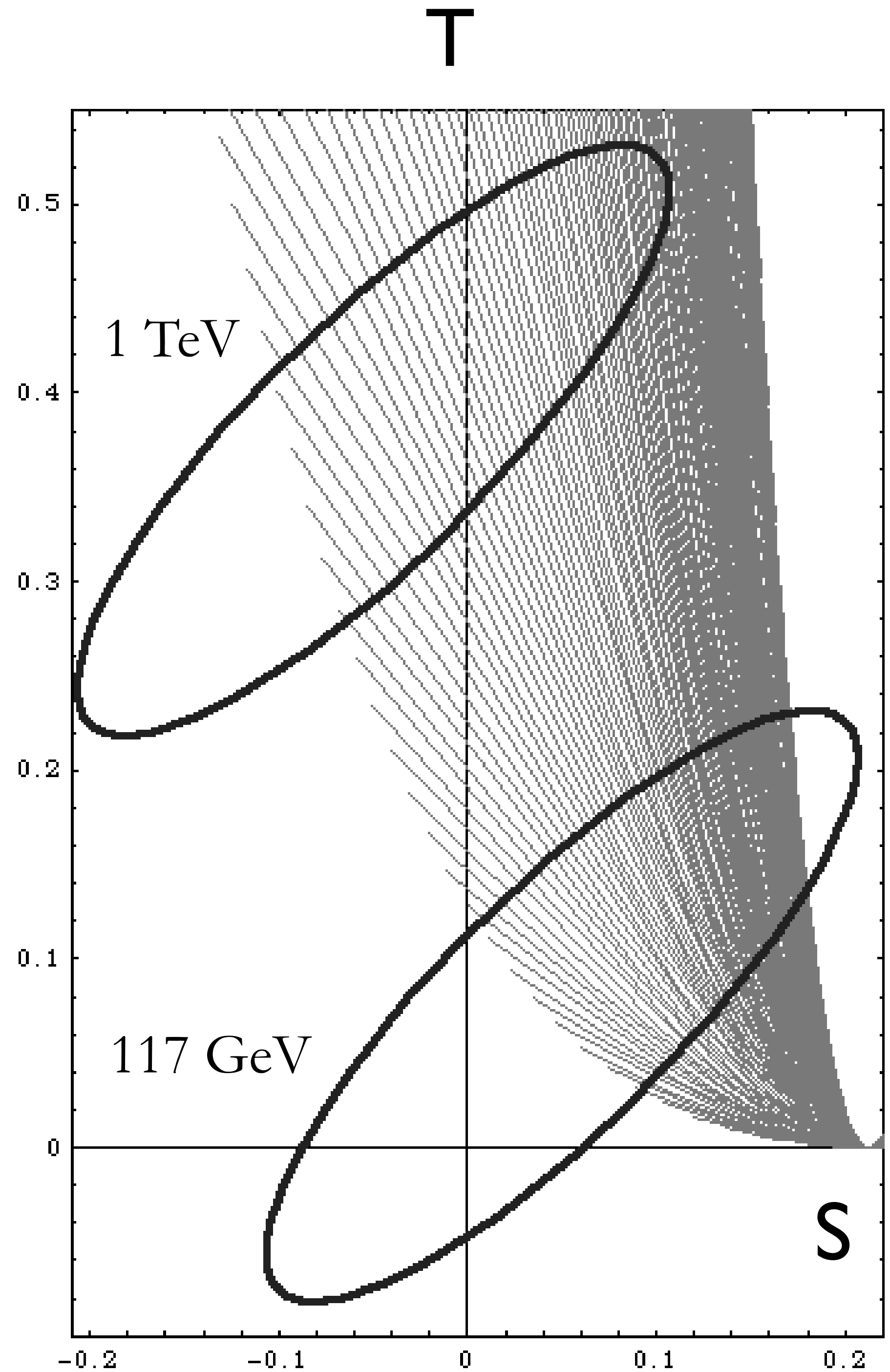
$$Y(Q_L) = \frac{y}{2} \qquad\qquad Y(U_R, D_R) = \left(\frac{y+1}{2}, \frac{y-1}{2}\right)$$

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

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

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

MWT versus EWPD



LEP EWG Summer 2006

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

Y=-3/2 for Leptons

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

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

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

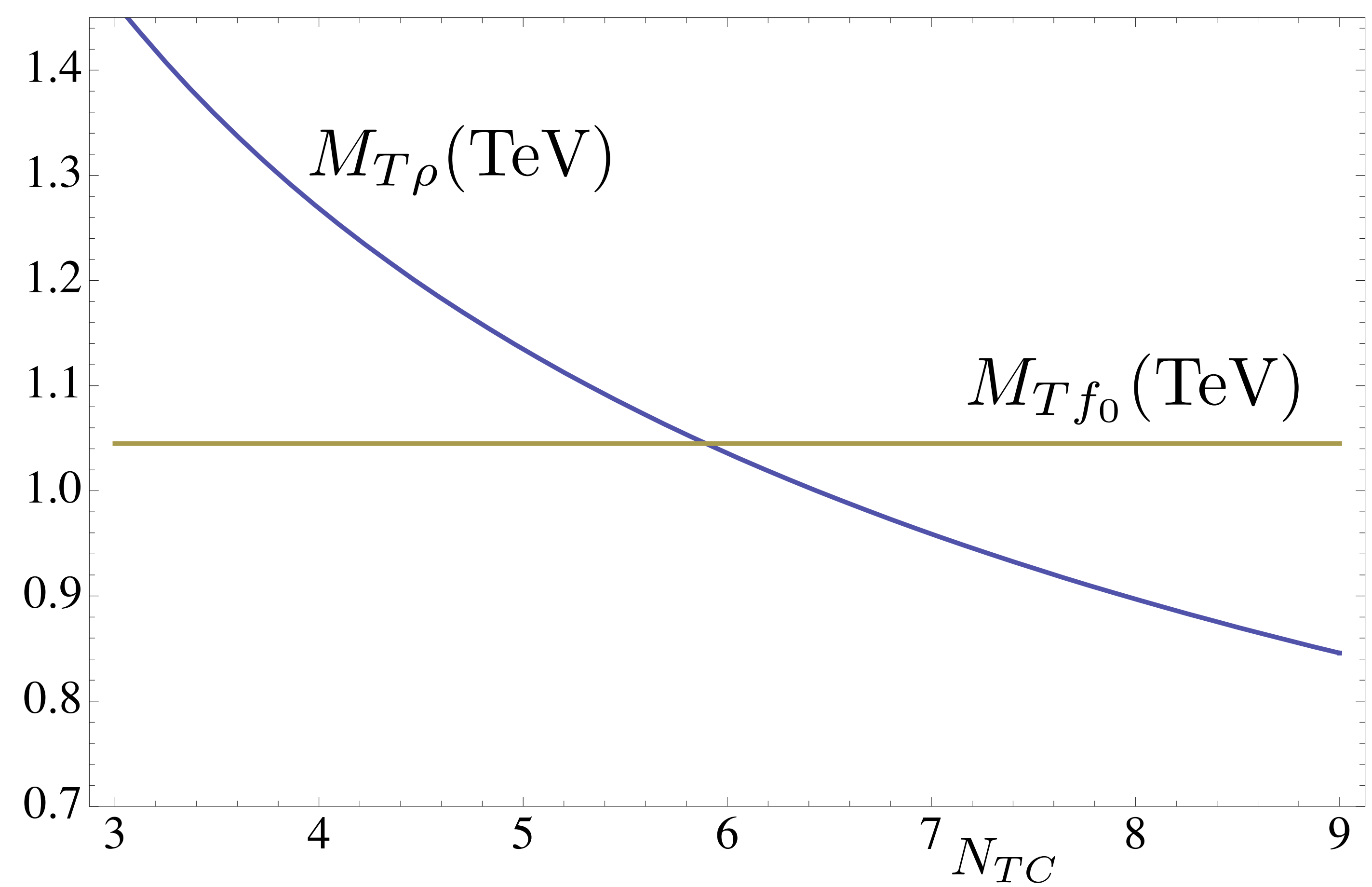
Higgsless: 't Hooft Extension

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

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

F.S. 07

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



$$N_D = 2$$

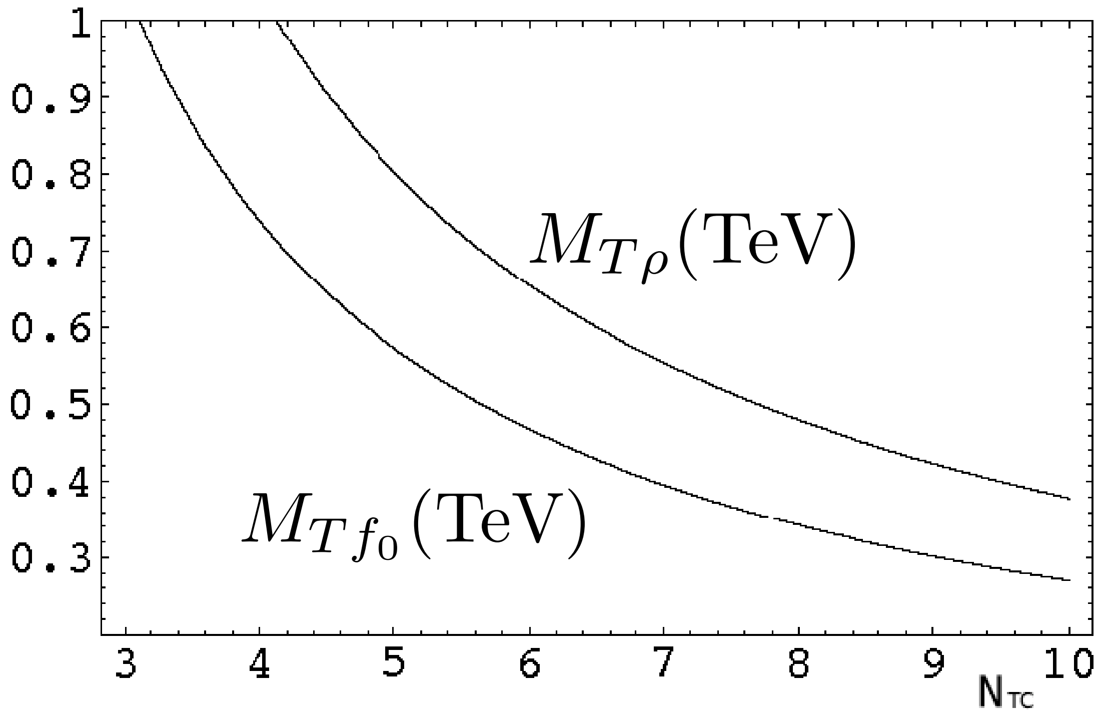
M_H/M_V < 1 in MWT theories

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

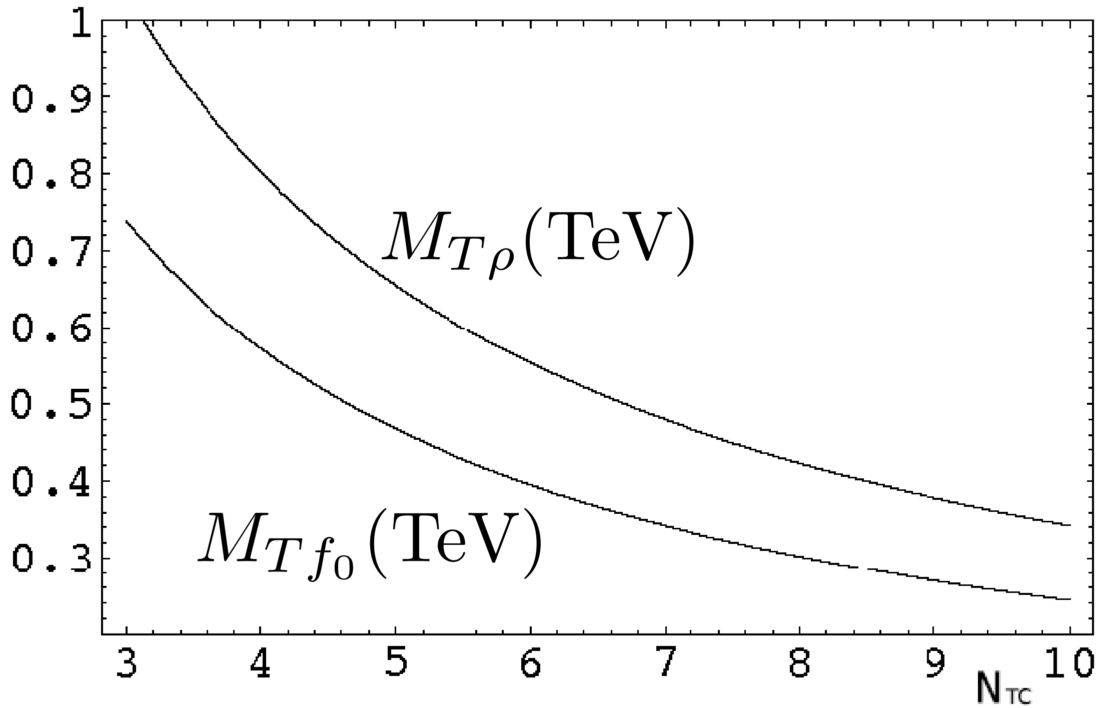
$$M_{Tf_0} = \frac{\sqrt{2}v_0}{F_\pi}\frac{\sqrt{3}\sqrt{2}}{\sqrt{N_D\,N_{TC}(N_{TC}\mp 1)}}m_{f_0}$$

F.S. 07

Antisymmetric



Symmetric



$N_D = 2$

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, Ryttov, 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

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

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

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

Conditions

Universe Electric Neutrality

Chemical Equilibrium

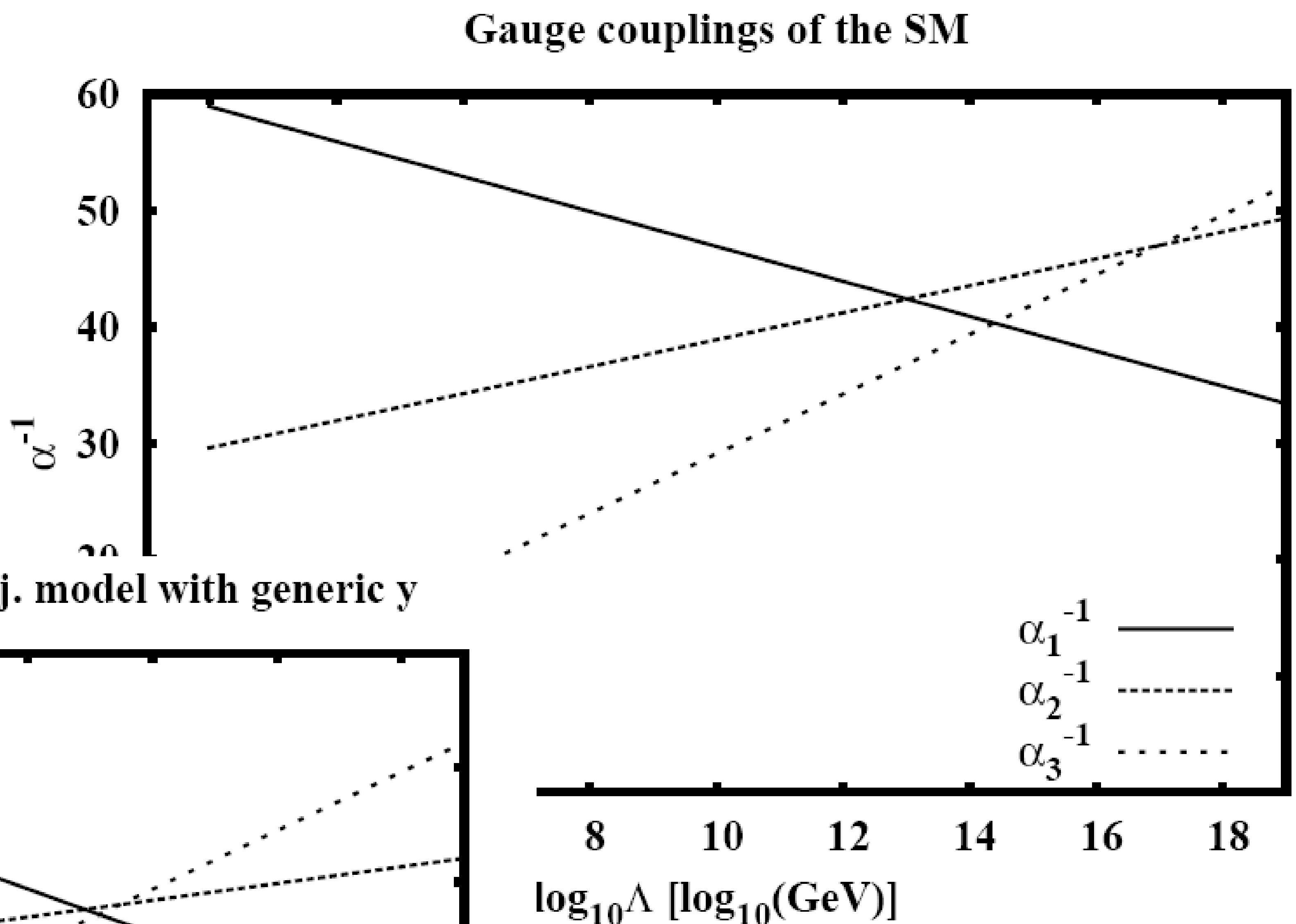
EW Sphaleron Processes, Kuzmin-Rubakov-Shaposhnikov

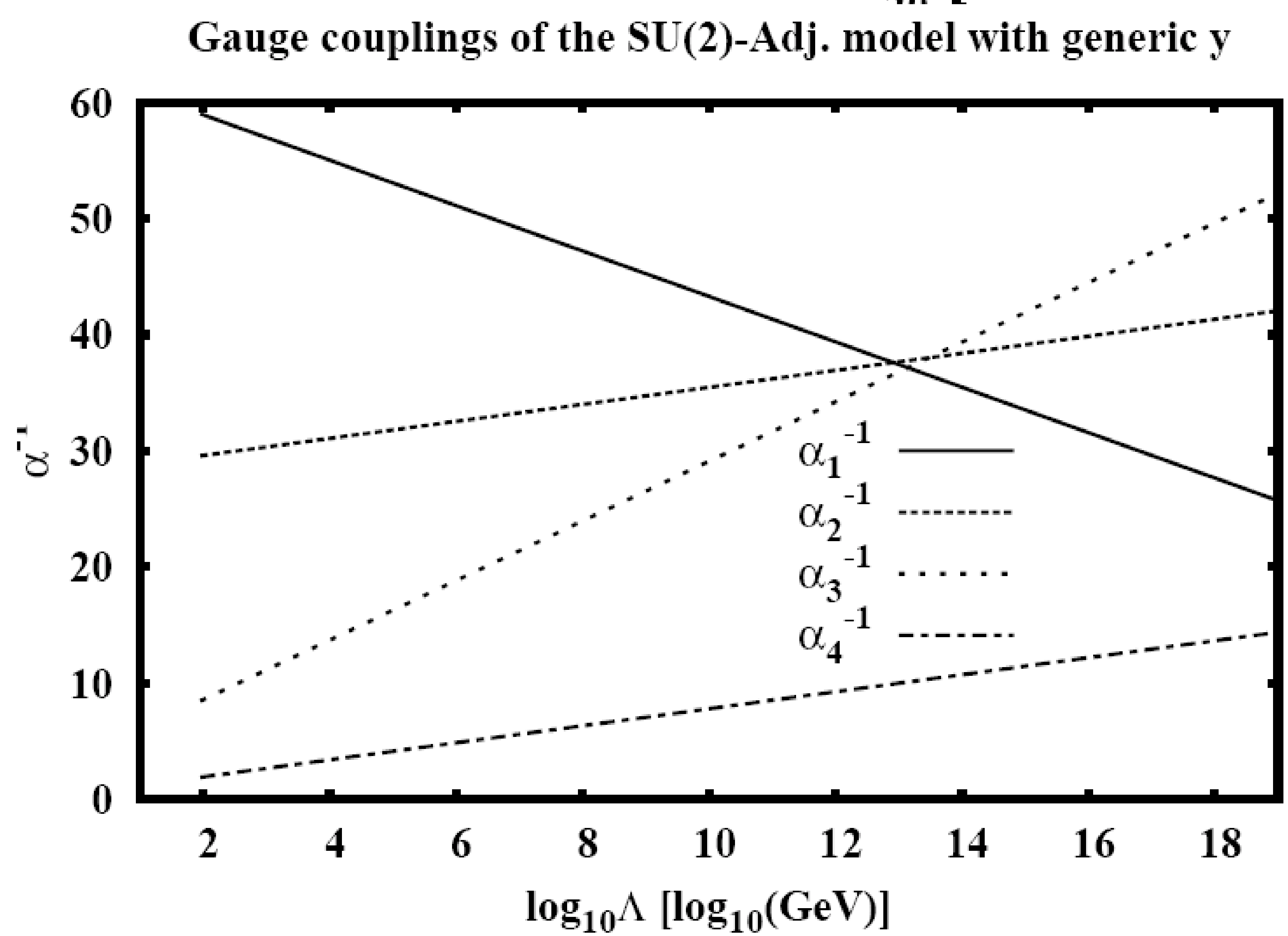
TB - B violated at High Energies & approx. conserved at EW

Playing with Unification

Farhi-Susskind, 79

Gudnason-Ryttov-F.S. 06

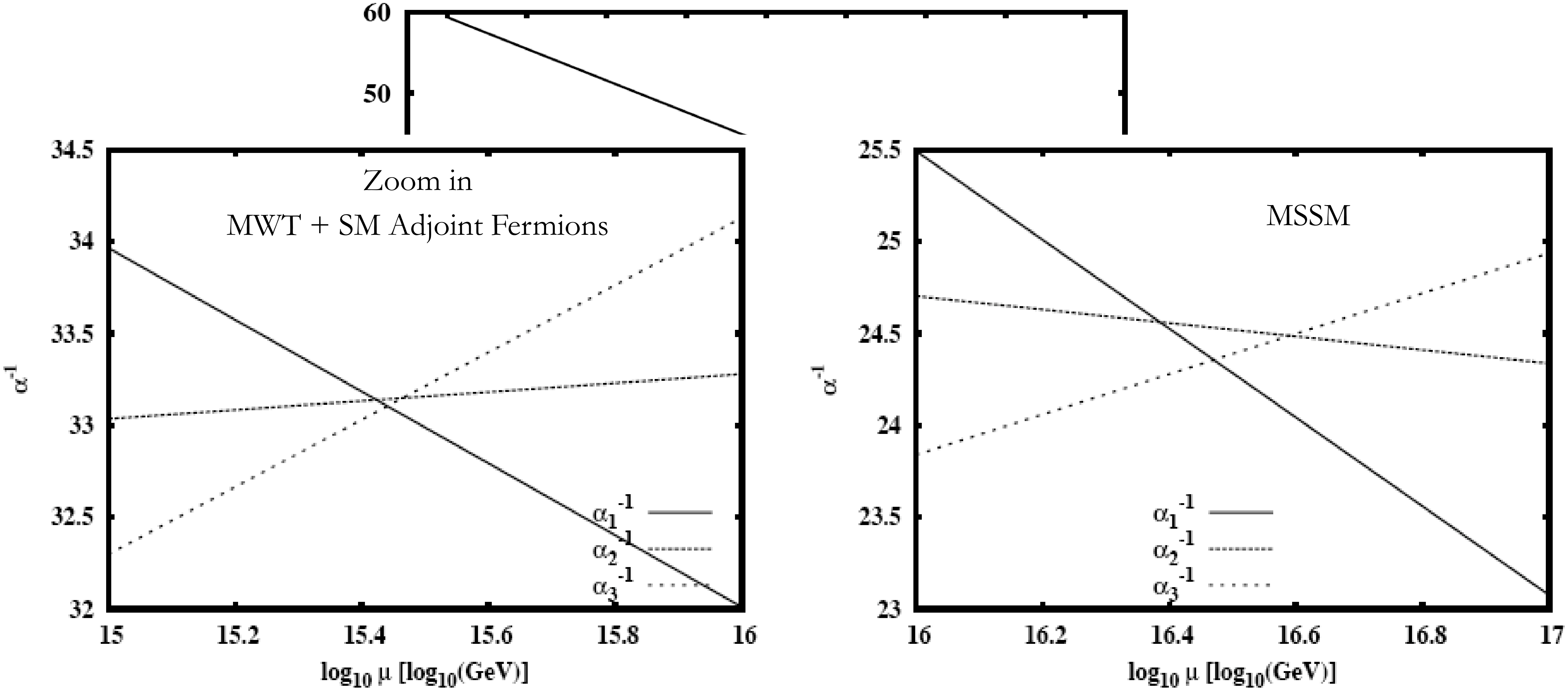

Gauge couplings of the SM
60
50
40
30
20
α^{-1}
α_1^{-1}
α_2^{-1}
α_3^{-1}
8
10
12
14
16
18
$\log_{10}\Lambda$ [$\log_{10}$(GeV)]


Gauge couplings of the SU(2)-Adj. model with generic y
60
50
40
30
20
10
0
α^{-1}
α_1^{-1}
α_2^{-1}
α_3^{-1}
α_4^{-1}
2
4
6
8
10
12
14
16
18
$\log_{10}\Lambda$ [$\log_{10}$(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

<u>A working technicolor benchmark</u>

Foadi, Frandsen, Ryttov & F.S. 07

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

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

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

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

$$\begin{aligned}
\mathcal{L}_{\text{Higgs}} &= \frac{1}{2}\mathrm{Tr}\left[D_\mu M D^\mu M^\dagger\right] + \frac{m^2}{2}\mathrm{Tr}[MM^\dagger] \\
&- \frac{\lambda}{4}\mathrm{Tr}\left[MM^\dagger\right]^2 - \lambda' \mathrm{Tr}\left[MM^\dagger MM^\dagger\right] + 2\lambda''\left[\mathrm{Det}(M) + \mathrm{Det}(M^\dagger)\right] \\
&+ \frac{m^2_{\text{ETC}}}{\Lambda}\,\mathrm{Tr}\left[MBM^\dagger B + MM^\dagger\right] \ ,
\end{aligned}$$

$$v^2 = \langle\sigma\rangle^2 = \frac{m^2}{\lambda + \lambda' - \lambda''}$$

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

$$\begin{aligned}
\mathcal{L}_{\text{Yukawa}} &= -\ y^{ij}_u\ q^{iT}\left(P_U M^*_{\text{off}} P_U\right) q^j - y^{ij}_d\ q^{iT}\left(P_D M^*_{\text{off}} P_D\right) q^j \\
&- y^{ij}_\nu\ l^{iT}\left(P_U M^* P_U\right) l^j - y^{ij}_e\ l^{iT}\left(P_D M^* P_D\right) l^j \\
&- y_N\ L^T\left(P_U M^*_{\text{off}} P_U\right) L - \ y_E\ L^T\left(P_D M^*_{\text{off}} P_D\right) L \\
&- \ y_{\widetilde{U}}\widetilde{Q}^T\left(P_U M^* P_U\right)\widetilde{Q} - \ y_{\widetilde{D}}\widetilde{Q}^T\left(P_D M^* P_D\right)\widetilde{Q}\ + \text{h.c.}
\end{aligned}$$

$$P_U = \begin{pmatrix} 1 & 0 \\ 0 & \frac{1+\tau^3}{2} \end{pmatrix} \qquad P_D = \begin{pmatrix} 1 & 0 \\ 0 & \frac{1-\tau^3}{2} \end{pmatrix}$$

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

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

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

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

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