Minimal Walking Technicolor and the Pseudo Goldstone Bosons

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CP^3 - Origins
Particle Physics & Origin of Mass

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Outline

- From QCD to Technicolor
- Walking Dynamics
- Minimal Walking Technicolor and PNGB
- Conclusions

QCD

Consider two flavor massless QCD

$$\mathcal{L} = -\frac{1}{4} F^a_{\mu\nu} F^{a,\mu\nu} + \bar{q}_L \left(i \not{D} \right) q_L + \bar{q}_R \left(i \not{D} \right) q_R$$

This Lagrangian has a $SU(2)_L \times SU(2)_R$ flavor symmetry

$$q_{L,R} \longrightarrow e^{-\theta^a_{L,R} \frac{\tau^a}{2}} q_{L,R}$$

Quarks and antiquarks are expected to form a condensate

$$\langle 0 | \bar{q} q | 0 \rangle = \langle 0 | \bar{q}_L q_R + \bar{q}_R q_L | 0 \rangle \neq 0$$

This implies a SSB

$$SU(2)_L \times SU(2)_R \rightarrow SU(2)_{L+R}$$

Gauging under the electroweak

Gauge $SU(2)_L \times U(1)_{3R} \subset SU(2)_L \times SU(2)_R$, where $U(1)_{3R}$ is generated by $\exp i\theta\tau_R^3/2$

$$U = \exp\left(i\vec{\pi}\cdot\tau/f_\pi\right) \qquad \mathcal{L} = \frac{f_\pi^2}{4}\mathrm{Tr}\left(|D_\mu U|^2\right) \qquad f_\pi = v$$

SSB $\longrightarrow$

$$M_Z = \frac{1}{2}\frac{g}{\cos\theta_w}v$$

$$M_W = \frac{1}{2}gv = \frac{e}{2\sin\theta_w}v$$

$$\rho = \frac{M_W^2}{M_Z^2\cos^2\theta_W} = 1$$

In QCD $v \sim 100$ MeV $\implies$ $M_W, M_Z \sim \mathcal{O}(10\ \mathrm{MeV})$

Technicolor

Copy/paste the idea and scale it up

Weinberg 1976, Susskind 1979

$$v_{\rm QCD} \to v_{\rm EW} = 246 \text{ GeV}$$

Gauge Group $SU(N_T) \times SU(3) \times SU(2)_L \times U(1)_Y$

Technifermions

$$Q_L^a = \begin{pmatrix} T \\ B \end{pmatrix}_L^a \qquad (Y = 0);$$

$$Q_R^a = (T_R,\ B_R)^a \qquad \frac{Y}{2} = (\frac{1}{2}, -\frac{1}{2}) \ .$$

Global symmetry $SU(2N_D)_L \times SU(2N_D)_R \to SU(2N_D)_D$

Scaling rules

Scaling rules for the QCD

$$f_\pi \sim \sqrt{N_c}\Lambda_{\rm QCD} \qquad \langle \bar{q}q \rangle \sim N_c \Lambda^3_{\rm QCD} \qquad m_{\rm fermion} \sim \Lambda_{\rm QCD}$$

In the case of N_D technifermion doublets

$$v \sim \sqrt{N_D} f_T \qquad\qquad f_T \sim \sqrt{\frac{N_T}{N_c}\frac{\Lambda_T}{\Lambda_{\rm QCD}}} f_\pi$$

Estimate for the TC scale

$$\Lambda_T \sim \Lambda_{\rm QCD} \frac{f_T}{f_\pi}\frac{N_c}{N_T} \sim v \frac{\Lambda_{\rm QCD}}{f_\pi}\sqrt{\frac{N_c}{N_D N_T}} \ \sim 10^2 - 10^3 \ \text{GeV}$$

Technicolor

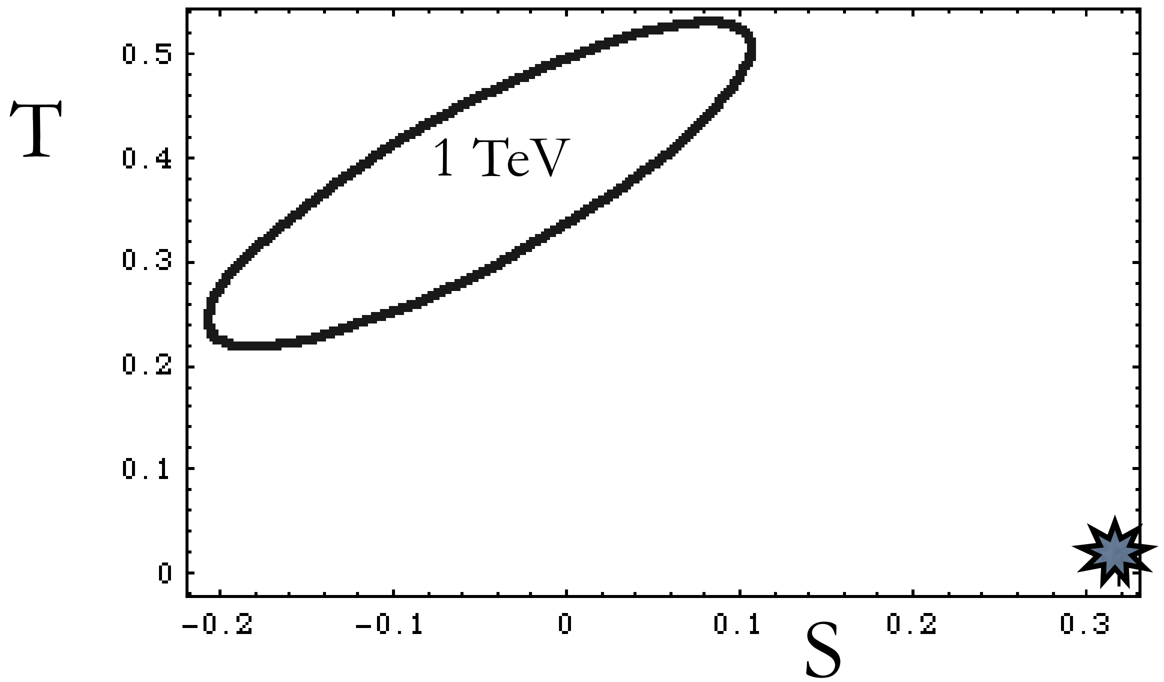
- Dynamical explanation of the EW scale
- No hierarchy/naturalness problem (better than SUSY)
- Mechanism already used by Nature

- Electro Weak Precision Test
- Fermion masses
- Flavor violation

Precision EW Data

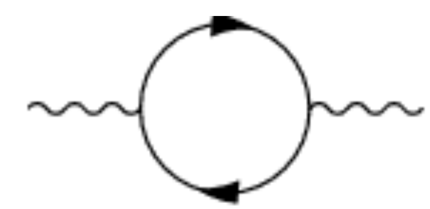
Large & Positive S from QCD-like Technicolor

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



Peskin and Takeuchi, 90

$$S_{\rm naive} = N_D \frac{d(R_{\rm TC})}{6\pi}$$



- Non perturbative quantity
- New operators from ETC can appear
- Walking dynamics helps
- Extra states can modify the pictures

Simmons et al, ..

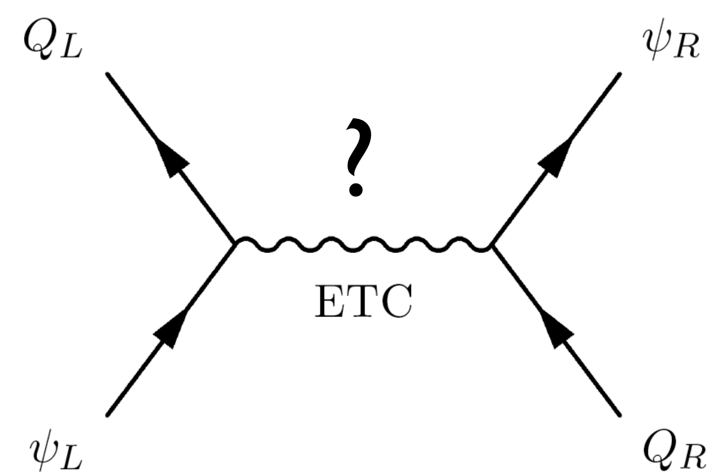
Appelquist and Sannino, 1999

Terning, Luty, Sundrum,

- TC models are not *a priori* ruled out
- More TC matter is gauged larger is the contribution to the S parameter

Extended Technicolor

Dimopoulos and Susskind 79, Eichten and Lane 80



$$m\bar{f}f = \frac{\langle\bar{Q}Q\rangle}{\Lambda^2_{\mathrm{ETC}}}\bar{f}f$$

- Fermion masses?

- Extended TC is needed

- Idea (Gauge interaction):

  1) Embed $G_{\mathrm{SM}} \times G_{\mathrm{TC}} \subset G_{\mathrm{ETC}}$

  2)TC-quarks and SM fermions connected via ETC gauge bosons

  3)Integrate out massive bosons

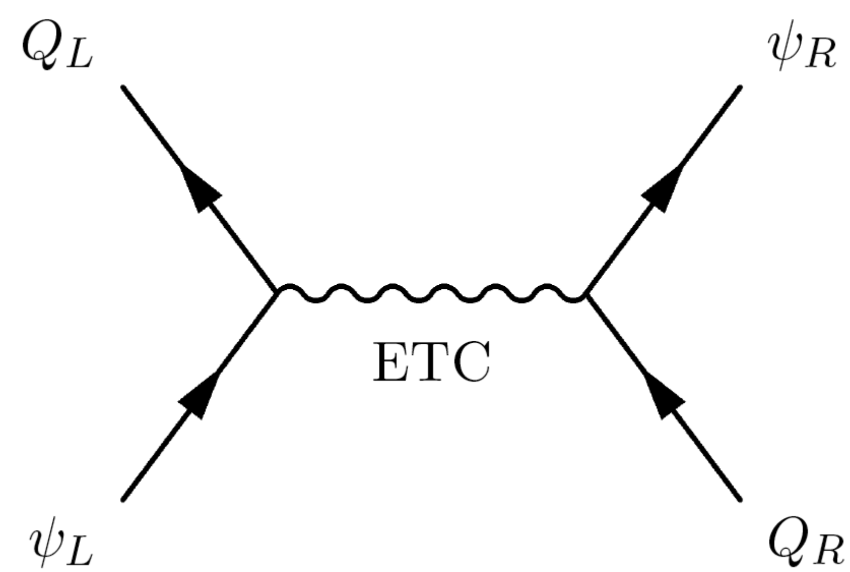
  $\longrightarrow$ Effective four fermion couplings

  4)Condensation of the TC-quarks produces a mass term

- Idea (Yukawa interaction): Bosonic Technicolor

Witten, Dine, Fischler, Srednicki, ...

Extended Technicolor



$$\alpha_{ab}\frac{\bar{Q}T^aQ\bar{Q}T^bQ}{\Lambda^2_{ETC}} + \beta_{ab}\frac{\bar{Q}_LT^aQ_R\bar{\psi}_RT^b\psi_L}{\Lambda^2_{ETC}} + \gamma_{ab}\frac{\bar{\psi}_LT^a\psi_R\bar{\psi}_RT^b\psi_L}{\Lambda^2_{ETC}} + \ldots$$

PNG Masses

SM-Fermion Masses

FCNC Operators

FCNC

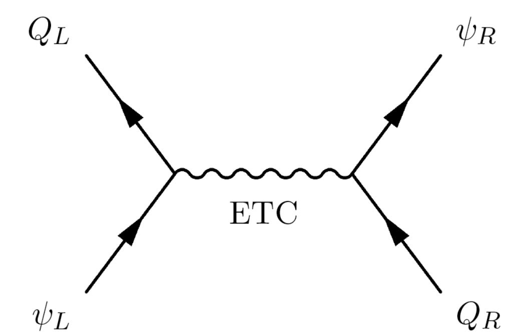
The third term is responsible for Flavor Changing Neutral Currents

$$\frac{1}{\Lambda_{\mathrm{ETC}}^2}(\bar{s}\gamma^5 d)(\bar{s}\gamma^5 d) + \frac{1}{\Lambda_{\mathrm{ETC}}^2}(\bar{\mu}\gamma^5 e)(\bar{e}\gamma^5 e) + \ldots$$

Measured value of the neutral Kaon mass splitting determines tight bound on the ETC scale

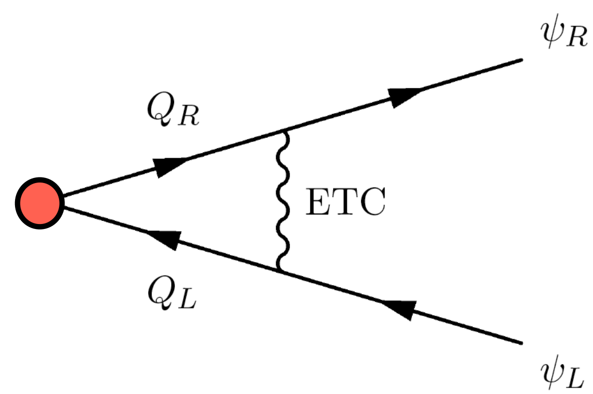
$$\frac{\Delta m^2}{m_K^2} \simeq \gamma_{sd}\frac{f_K^2 m_K^2}{\Lambda_{ETC}^2} \lesssim 10^{-14} \Rightarrow \Lambda_{ETC} \gtrsim 10^3 \text{ TeV}$$

Fermion masses



Energy

Λ_{ETC}



$$m_{\mathrm{f}} \approx \frac{g^2_{ETC}}{\Lambda^2_{ETC}} < \bar{Q}Q >_{ETC}$$

Λ_{TC}

Electroweak

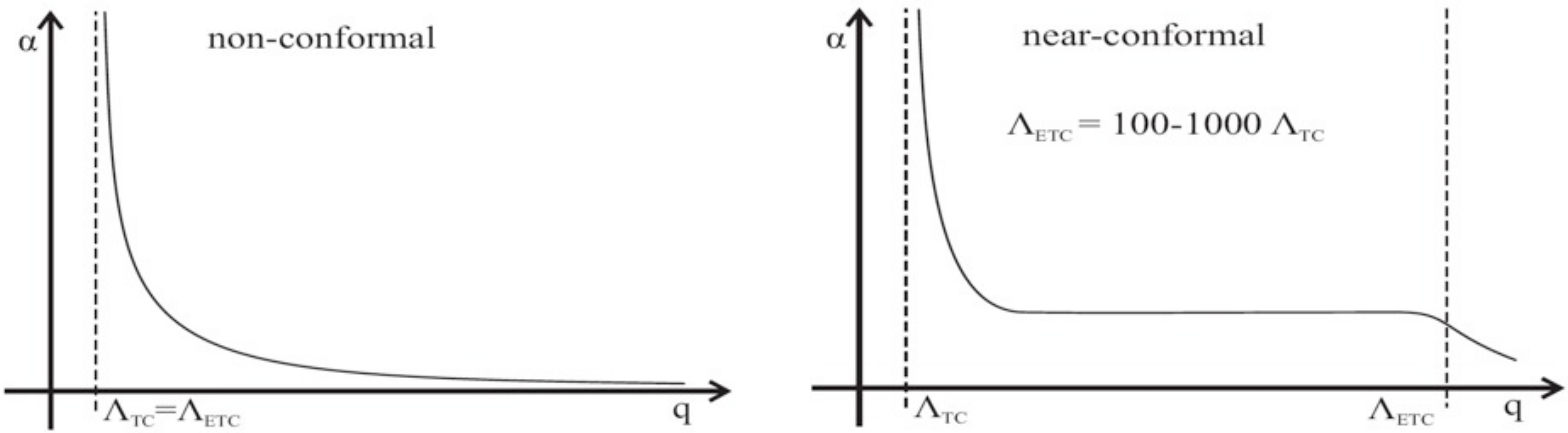
$$< \bar{Q}Q >_{ETC} \approx < \bar{Q}Q >_{TC} \sim \Lambda^3_{TC}$$

$$\boxed{m_{\mathrm{f}} \approx \frac{g^2_{ETC}}{\Lambda^2_{ETC}} < \bar{Q}Q >_{ETC} \quad \ll \quad m_{\mathrm{Top}}}$$

$$\Lambda_{ETC} \gtrsim 10^3 \text{ GeV} \longrightarrow m_{\mathrm{f}} \lesssim 100 \text{ MeV}$$

New type of dynamics

Holdom 81



$$m_{\rm f} \approx \frac{g_{ETC}^2}{\Lambda_{ETC}^2} < \bar{Q}Q >_{ETC} = \frac{g_{ETC}^2}{\Lambda_{ETC}^2} \left(\frac{\Lambda_{ETC}}{\Lambda_{TC}}\right)^{\gamma_m(\alpha^*)} < \bar{Q}Q >_{TC}$$

- Fixed points give walking behavior
- Large anomalous dimension are needed (for the top mass $\gamma_m(\alpha^*) \approx 1.7$)
- Schwiger-Dyson analysis leads to $\gamma_m(\alpha^*) \approx 1$
- TC is not a theory in isolation (four Fermi interactions can change the picture)

Guidelines for a TC model

Guidelines for model building:

- Theory with a strongly interacting fixed point (Walking dynamics)
- Small number of EW doublets

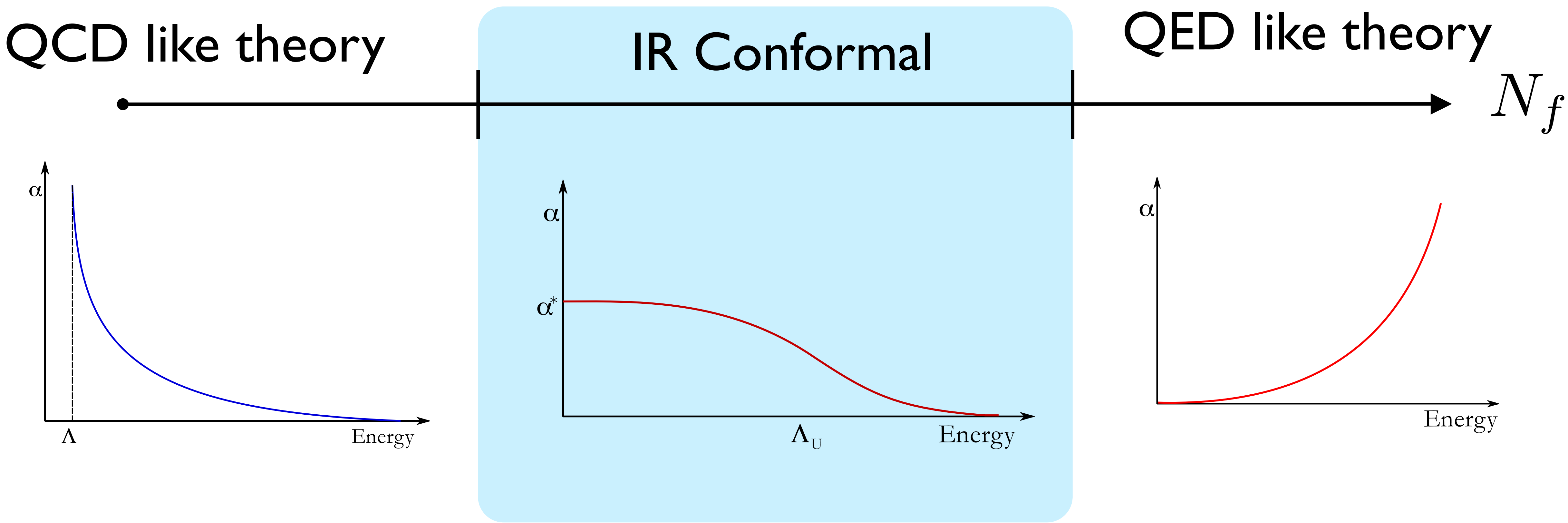
$$S_{\rm naive} = \frac{d(r) N_f}{12\pi}$$

Gauge Group, i.e. SU, SO, SP

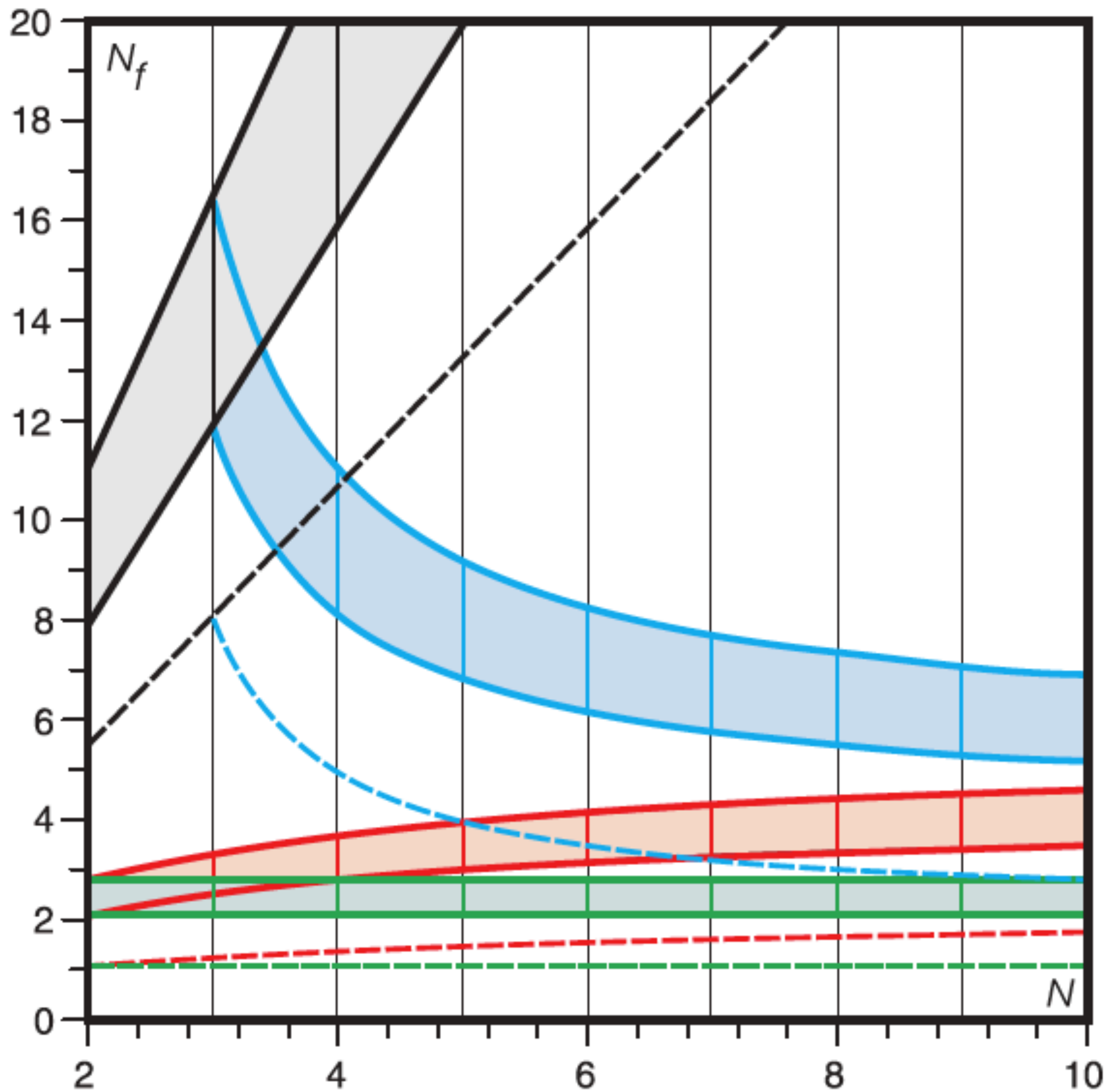
Matter Representation

# of Flavors and # of Technicolors

Conformal Window



SU(N)



- Fundamental
- Two-index antisymmetric
- Two-index symmetric
- Adjoint

Minimal models of Technicolor

- Minimal WT

$SU(2)_{TC}$ $\square\square$ **U D** **N E**

Sannino, Tuominen 04

Dietrich, Sannino, Tuominen 05

- Next to MWT

$SU(3)_{TC}$ $\square\square$ **U D**

Sannino, Tuominen 04

Dietrich, Sannino, Tuominen 05

- Orthogonal

$SO(4)_{TC}$ $\square$ **U D**

Frandsen, Sannino 09

- Ultra MT

$SU(2)_{TC}$ $\square$ **U D**

Ryttov, Sannino 08

- Other models/ETC

Farhi and Susskind 79;
Eichten and Lane 89;
Appelquist and Terning 94;
Appelquist, Christensen, Pia and Shrock 04
Evans and Sannino 08
Ryttov and Shrock 09,10
Conformal Techicolor, Luty

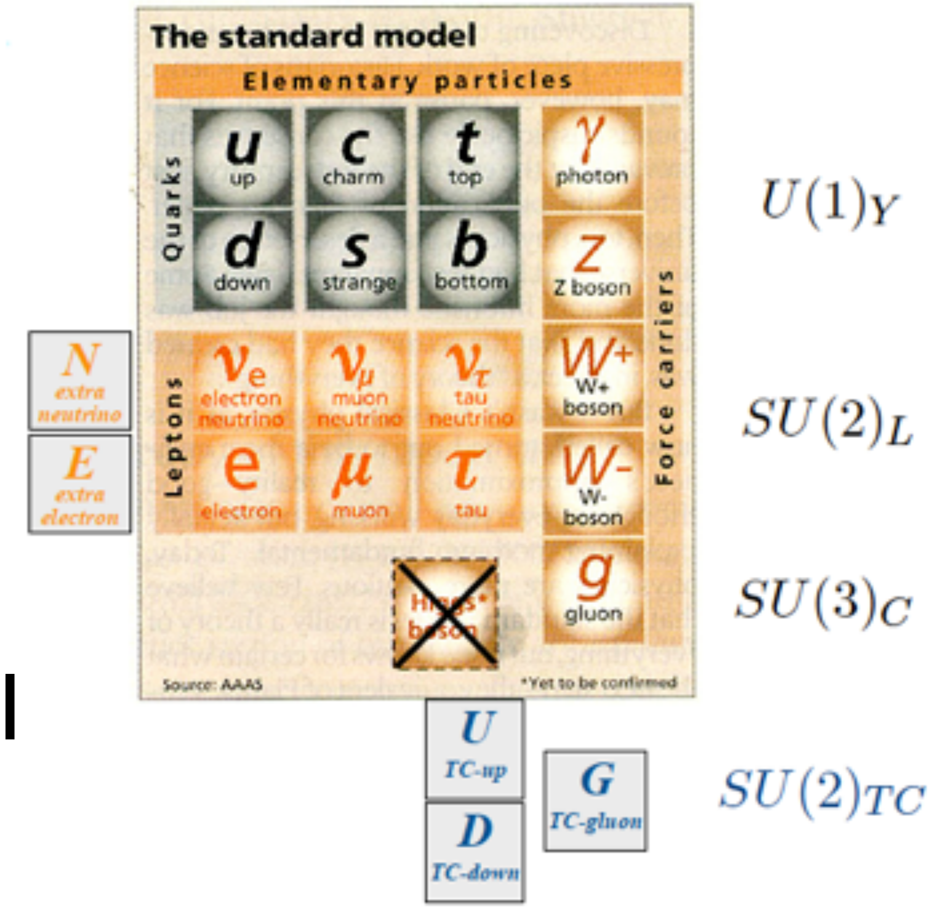
- Effective Theories

Appelquist, Da Silva, Sannino 99;
Da Silva, Duan, Sannino. 99
Foadi, Frandsen, Ryttov, Sannino 07
Lane and Martin 09

MWT

TC-fermions in the adjoint of $SU(2)_{\mathrm{TC}}$

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



All the rep. of SU(2) are real or pseudo-real

$$Q = \begin{pmatrix} U_L \\ D_L \\ -i\sigma^2 U_R^* \\ -i\sigma^2 D_R^* \end{pmatrix} \longrightarrow \text{SU(4) global symmetry}$$

- Model **hep-ph/0405209, hep-ph/0505059**
- Linear realization **0706.1696,**
- Spin-one phenomenology **0809.0793, 1104.1255, 1105.1433**
- Lattice **0705.1664, 0807.0792**

Anomalies

To cancel the Witten anomaly

$$L_L = \begin{pmatrix} N \\ E \end{pmatrix}_L , \qquad N_R \, , \, E_R$$

Anomaly free hypercharge content

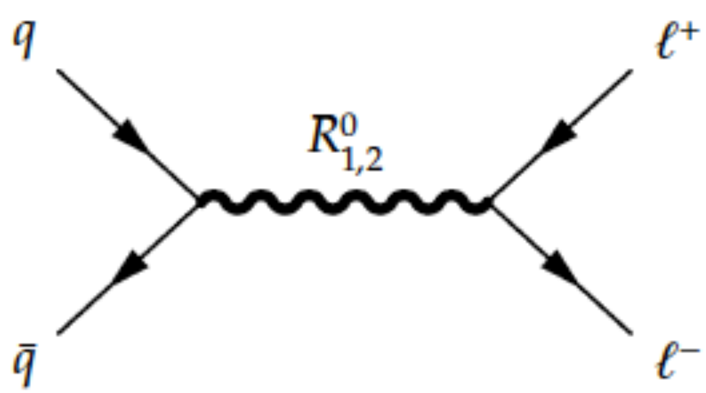
$$Y(Q_L) = \frac{y}{2} \, , \qquad Y(U_R, D_R) = \left(\frac{y+1}{2}, \frac{y-1}{2} \right) ,$$

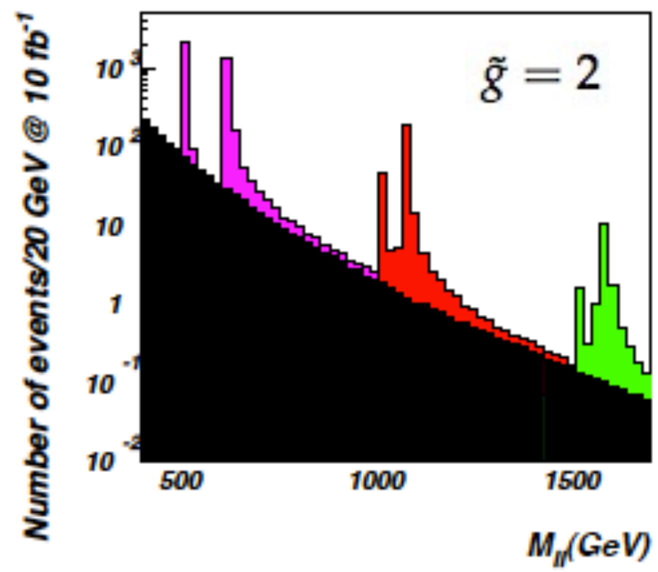
$$Y(L_L) = -3\frac{y}{2} \, , \qquad Y(N_R, E_R) = \left(\frac{-3y+1}{2}, \frac{-3y-1}{2} \right)$$

- y is restricted to be odd in order to avoid stable fractionally charged states
- From now on let me fix y=1

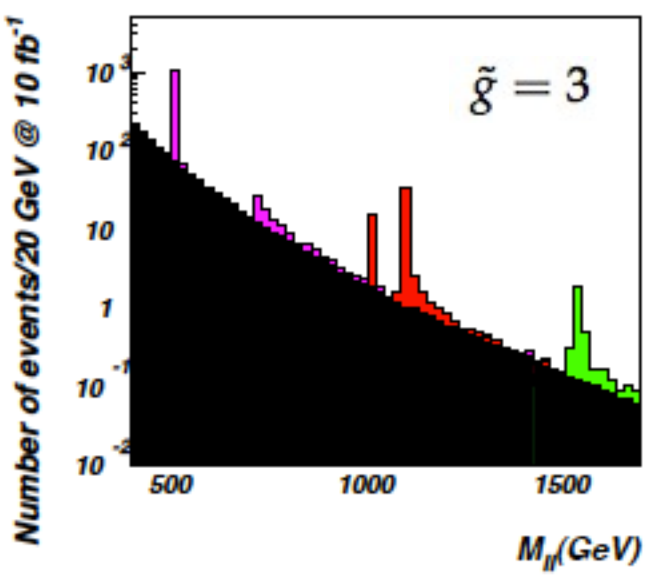
Signatures

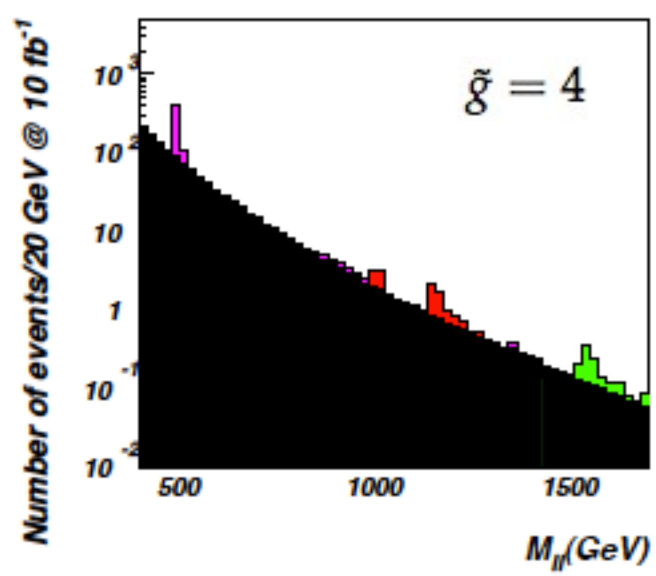
$pp \to R_{1,2} \to \ell^+\ell^-$





7 TeV

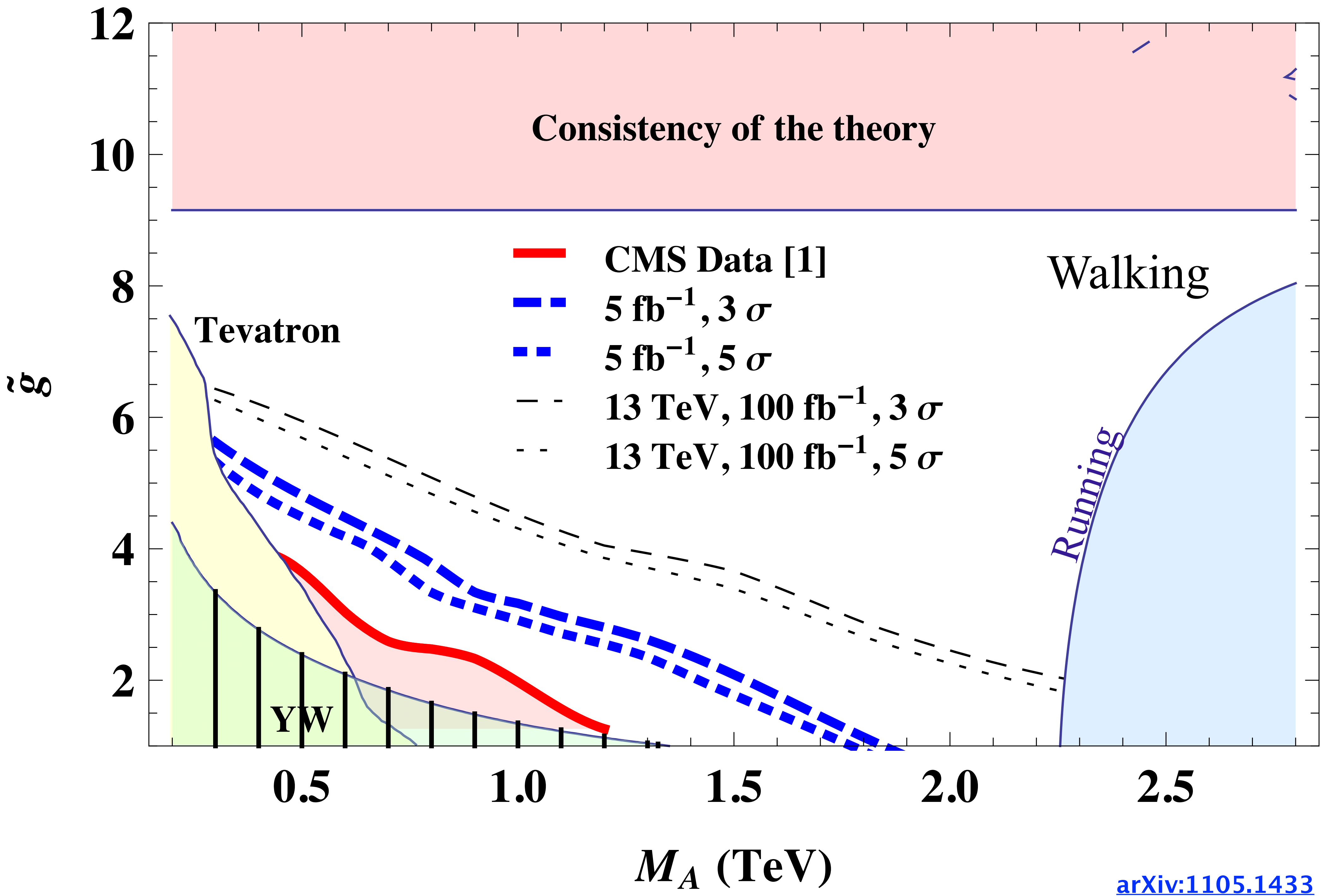




arXiv:1104.1255

Andersen, Del Nobile, TH, Sannino, ...

Excluding Parameter Space



arXiv:1105.1433

Andersen, TH, Sannino

Symmetry breaking

Symmetry breaking SU(4) $\longrightarrow$ SO(4)

$$Q = \begin{pmatrix} U_L \\ D_L \\ -i\sigma^2 U_R^* \\ -i\sigma^2 D_R^* \end{pmatrix}, \qquad \langle Q_i^\alpha Q_j^\beta \epsilon_{\alpha\beta} E^{ij} \rangle = -2 \langle \overline{U}_R U_L + \overline{D}_R D_L \rangle \qquad E = \begin{pmatrix} 0 & \mathbb{1} \\ \mathbb{1} & 0 \end{pmatrix}$$

\# NG Bosons = 15 - 6 = 9 = 3+6

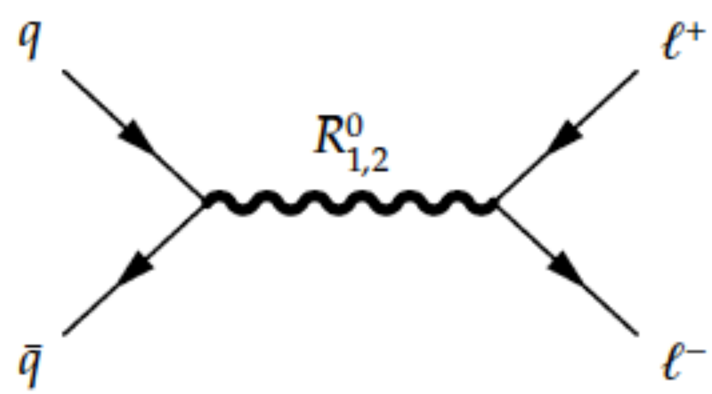
Uneaten Goldston: $\Pi_{+2}, \Pi_{+1}, \Pi_0 + \text{h.c}$

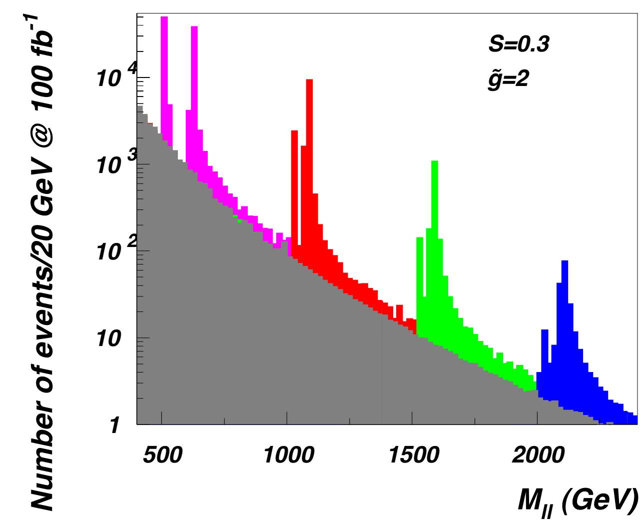
$$U = \exp\left(i \frac{\sqrt{2}}{F} \Pi^a X^a \right) E \longrightarrow L = \frac{F^2}{2} \mathrm{Tr}\left[D_\mu U D^\mu U^\dagger \right]$$

Motivation to study PNGBs

- Based on a work in collaboration with M. Nardecchia, F. Sannino (CP3-Origins) and F. Mescia (Universitat de Barcelona)

$$pp \to R^0_{1,2} \to l^+ l^-$$





- Common lore: strongly interacting signature associated to spin-1
- Minimal pattern of symmetry breaking: $SU(2)_L \otimes SU(2)_R \to SU(2)_V$
- No PNGB!
- Larger symmetry breaking group are naturally motivated
- Minimal Walking Technicolor (MWT) leading to the breaking $SU(4) \to SO(4)$.
- PNGB 15-6=9=3+6

Conclusions

- Dynamical EWSB can naturally occur at the LHC
- Walking Dynamics alleviates flavor and EWPT problems
- Minimal Walking Technicolor is a well motivated example
- Pseudo Nambu-Goldstone Bosons can be the first signal from strong dynamics