# Beyond the Standard Model

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# Big Picture

Three major paradigms for particle physics beyond the standard model

- Supersymmetry   "Logos"

  From the Greek: reason, word

- Strong dynamics, extra dimensions   "Stratus"

  From the Latin: a cover or spread; low-lying clouds

- Multiverse   "Chaos"

  From the Greek: formlessness, confusion

# Outline

"It is better to uncover a little, than to cover a lot."
V. Weisskopf

1. Motivation for new physics at the TeV scale
2. Strong Higgs sector
3. Composite Higgs/Little Higgs
4. Extra dimensions
5. Multiverse

# Motivation

# Effective Field Theory

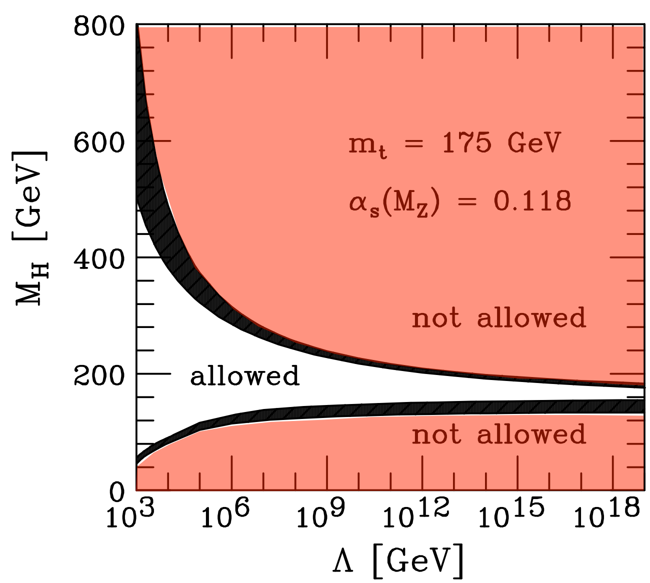
An old idea: approximate theory using only degrees of freedom that can be excited at low energy

E.g. QED $(e^{\pm}, \gamma)$ valid for $E \ll m_\mu$

Standard model breaks down at high energies

$\Rightarrow$ must be effective theory

- Gravity: $M_{\text{Planck}} \sim 10^{19}\ \text{GeV}$
- Higgs self-interactions




(Hambye, Riesselmann 1997)

Also lots of concrete motivation for physics beyond standard model

Neutrinos, dark matter, baryogenesis, strong CP problem, gauge coupling unification, origin of flavor,...

# Effective Standard Model

What effective theory describes our present understanding of strong/electroweak physics?

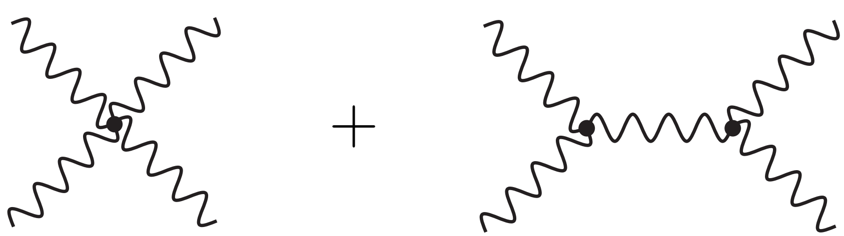
Not the standard model! We haven't found the Higgs...

$$\mathcal{L}_{\text{eff}} = \mathcal{L}_{\text{SM}}(\cancel{h^0}, A_\mu, W_\mu^\pm, Z_\mu, G_\mu, q, \ell) \qquad \text{(unitary gauge)}$$

Equivalent to nonlinearly realized $SU(2)_W \times U(1)_Y \to U(1)_{\text{EM}}$

Expansion in powers of $\dfrac{E}{4\pi v} \sim \dfrac{E}{\text{TeV}}$

Example: WW scattering



$$+ \qquad \sim E^2$$

$$\sim \cancel{E^4} + E^2 + \cdots \qquad \sim \cancel{E^4} + E^2 + \cdots$$

# Higgs Sector

Effective standard model breaks down at TeV scale

$\Rightarrow$ new physics below TeV!

Higgs boson is only one possibility...

Maybe the only appearance of Higgs at LHC

# Naturalness

Not a question of "canceling UV divergences..."

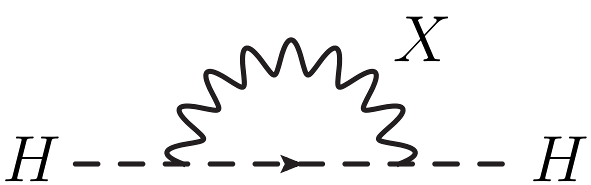
Dependence of effective parameters on (more) fundamental ones

$$\mathcal{L}_{\rm SM} = -m_H^2 H^\dagger H + \cdots$$

$H^\dagger H$ invariant under all symmetries*

$\Rightarrow$ $m_H \sim$ scale of new physics

E.g. grand unification:



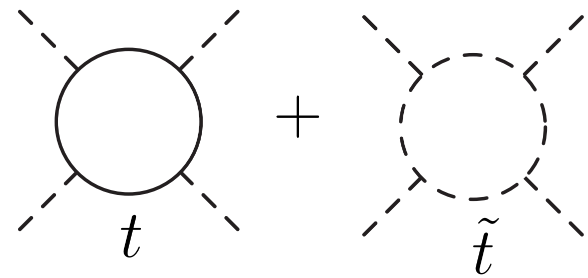

$$\Rightarrow \Delta m_H^2 \sim \frac{g_{\rm GUT}^2}{16\pi^2} M_X^2 \sim (10^{15}\ {\rm GeV})^2$$

*Except supersymmetry

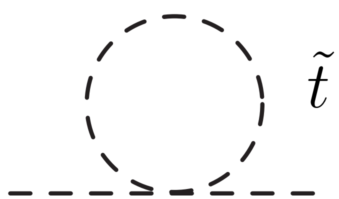
# Is SUSY Natural?

Higgs quartic coupling: $\lambda \sim g^2 + \underbrace{\frac{3y_t^4}{16\pi^2} \ln \frac{m_{\tilde{t}}}{m_t}}$

$$\Rightarrow m_{h^0}^2 \sim \lambda v^2 \sim m_Z^2 + \frac{3y_t^4 v^2}{16\pi^2} \ln \frac{m_{\tilde{t}}}{m_t}$$




$m_{h^0}^2 > 114 \text{ GeV}$ requires $m_{\tilde{t}} \gtrsim 1 \text{ TeV}$




$$\Rightarrow \Delta m_H^2 \sim \frac{3y_t^2}{16\pi^2} m_{\tilde{t}}^2 \sim (1 \text{ TeV})^2$$

⇒ 1% tuning in MSSM

Exactly the problem SUSY was meant to solve...

# Naturalness Sector

Naturalness breaks down at TeV scale
$\Rightarrow$ new physics at TeV scale?

- SUSY?
- Strong electroweak symmetry breaking?
- Composite Higgs?

All have problems...

- Just the standard model?

# Dark Matter

Another hint for new physics at the TeV scale

Thermal weak-scale relic $\Rightarrow$ $\Omega \sim 0.1 \left( \frac{\sigma_{\rm ann} v}{\rm pb} \right)^{-1}$

Standard collider signature: missing energy

Many models, wide range of predictions

(including no collider signatures)

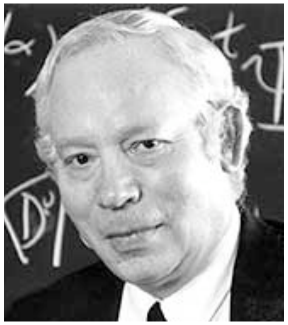
# Summary

Expect new physics at TeV colliders

| | |
|---|---|
| • Higgs sector | Required |
| • Naturalness sector | Highly recommended |
| • Dark matter | Suggested |

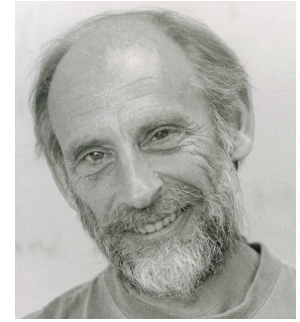
Anything else is a welcome surprise...

# Strong Higgs Sector



# Classic Technicolor

Weinberg 1976; Susskind 1976



Copy QCD...

New $SU(N)$ gauge force strong at TeV scale

$$\Psi_L = \underbrace{\begin{pmatrix} U_L \\ D_L \end{pmatrix}}_{SU(2)_W} \qquad \Psi_R = \underbrace{\begin{pmatrix} U_R \\ D_R \end{pmatrix}}_{SU(2)_W}$$

doublet singlet

$$Y(U_R) = Y(\Psi_L) + \tfrac{1}{2}$$
$$Y(D_R) = Y(\Psi_L) - \tfrac{1}{2}$$

$$\langle \bar{\Psi}_{La} \Psi^b_R \rangle = \Lambda^3_{\rm TC} \delta_a{}^b \qquad \Lambda_{\rm TC} \sim \rm TeV$$

$$\bar{\Psi}_L U_R \sim H$$
$$\bar{\Psi}_L D_R \sim H^*$$

$\Rightarrow$ same symmetry breaking pattern as SM

# Is Technicolor Natural?

$$\mathcal{L}_{\mathrm{TC}} = -\frac{1}{4} H^{\mu\nu A} H_{\mu\nu A} + \bar{\Psi} i \not{D} \Psi$$

No singlet operator with dimension < 4

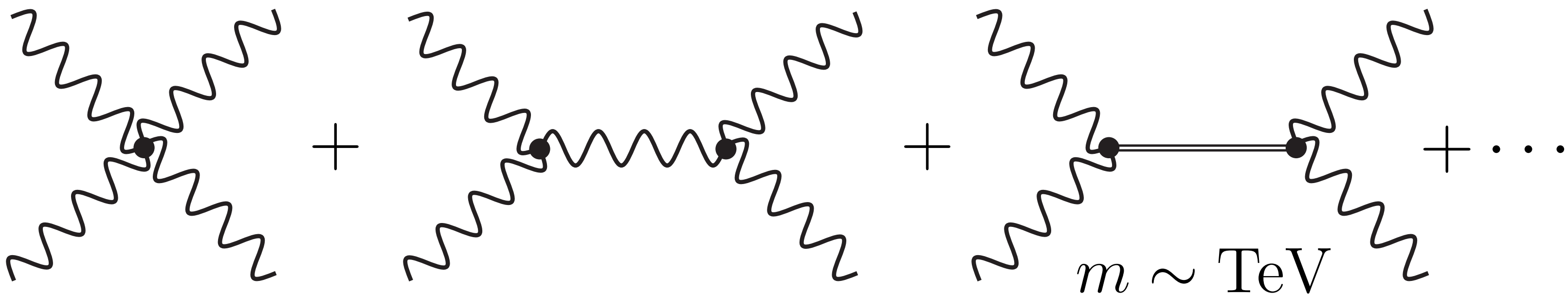
(c.f. $\mathcal{L}_{\mathrm{SM}} = -m_H^2 H^\dagger H + \cdots$)

Technifermion mass $\bar{\Psi}\Psi$ forbidden by gauge invariance

# Technicolor Signatures

Higgs sector = strong TeV resonances

E.g. WW scattering




QCD suggests vector resonances most prominent

Spin 0 “composite Higgs” may be absent or obscure

$\boxed{f_0(600) \text{ or } \sigma}$ $\qquad I^G(J^{PC}) = 0^+(0^{++})$

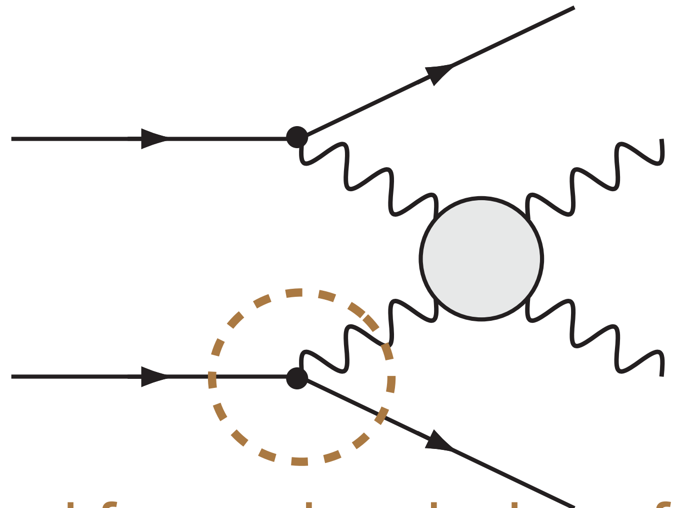
**$f_0(600)$ T-MATRIX POLE $\sqrt{s}$**

Note that $\Gamma \approx 2\ \mathrm{Im}(\sqrt{s_{\mathrm{pole}}})$.

| VALUE (MeV) | DOCUMENT ID | TECN | COMMENT |
|---|---|---|---|
| **(400–1200)$-i$(250–500) OUR ESTIMATE** | | | |

PDG 2010

# WW Scattering @ LHC





A model-independent signal for strong Higgs sector

(Chanowitz, Gaillard 1984)

| Cut | Value for keeping events |
|---|---|
| Leptonic W $P_T$ | $P_T > 320$ GeV |
| Hadronic W $P_T$ | $P_T > 320$ GeV |
| Hadronic W mass | $66.09 < M < 101.89$ GeV |
| Y-scale | $1.55 < \mathrm{Y-scale} < 2.0$ |
| Top veto | $130 < \mathrm{M_{W+jet}} < 240$ GeV |
| Tag Jets | $P_T > 20$ GeV, $E > 300$ GeV, $2.0 < \lvert\eta\rvert < 4.5$ |
| Hard Scatter $P_T$ | $P_T < 50$ GeV |
| Number of mini-jets ($P_T > 15$ GeV with $\lvert\eta\rvert < 2.0$) | 0 |

5σ discovery with 30 $fb^{-1}$ for models with resonances

E. Stefanidis ATLAS Thesis (2007)

# Problems with Technicolor

- Top quark
- Flavor mixing
- Precision electroweak

# Flavor in Technicolor

Standard model $\to$ technicolor

$H \to \bar{\Psi}\Psi \qquad (\dim(\bar{\Psi}\Psi) = 3$ solves naturalness problem)

$$\mathcal{L}_{\text{SM}} = y_t \bar{Q}_L H t_R + \cdots \;\to\; \frac{1}{\Lambda_t^2} \underbrace{(\bar{Q}_L t_R)(\bar{\Psi}\Psi)}_{\dim\, =\, 6} + \cdots$$

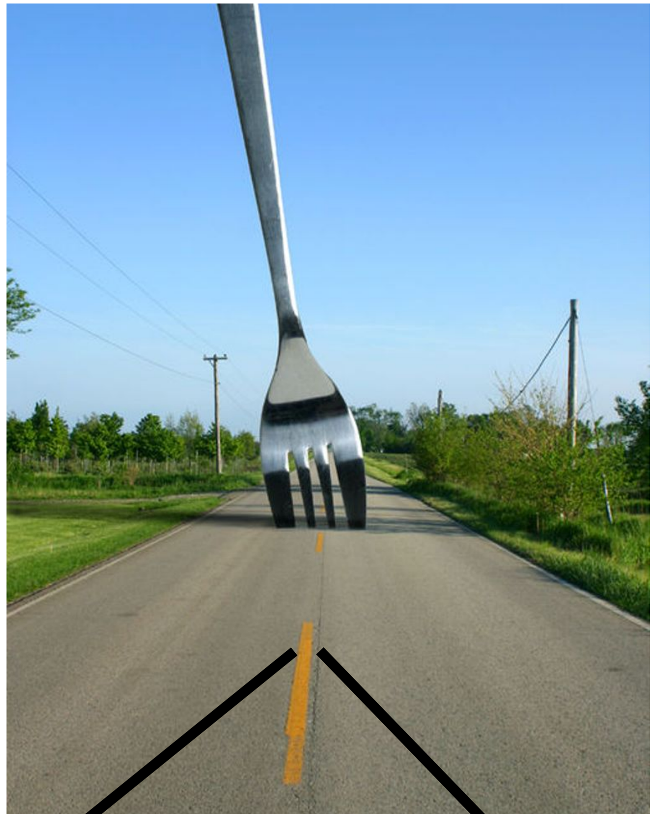
Effective 4-fermion interaction can arise from heavy particle exchange (c.f. Fermi theory)

$\Lambda_t =$ scale where effective flavor theory breaks down

$\sim$ few TeV

$\Rightarrow$ must address flavor near TeV scale

# Top in Technicolor



Topcolor

Hill 1991

Walking/conformal technicolor

# Conformal Technicolor

$H =$ operator in Higgs sector

Consider general values of $d = \dim(H)$

- $d \geq 1$ (unitarity)
- $\dim(\bar{Q}_L H t_R) = 3 + d$

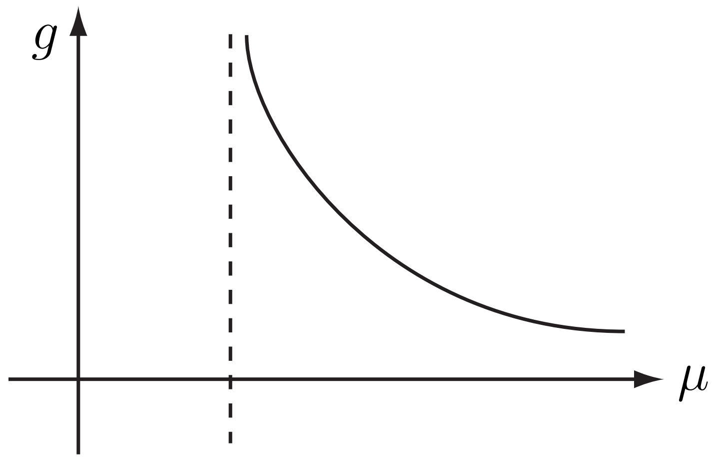
  $\Rightarrow$ want $d$ as small as possible
- Want $\underbrace{\dim(H^\dagger H) \geq 4}_{\Rightarrow\, d \leq 2\,?}$ (naturalness)

  Not necessarily...

Possible in conformal (scale invariant) theories

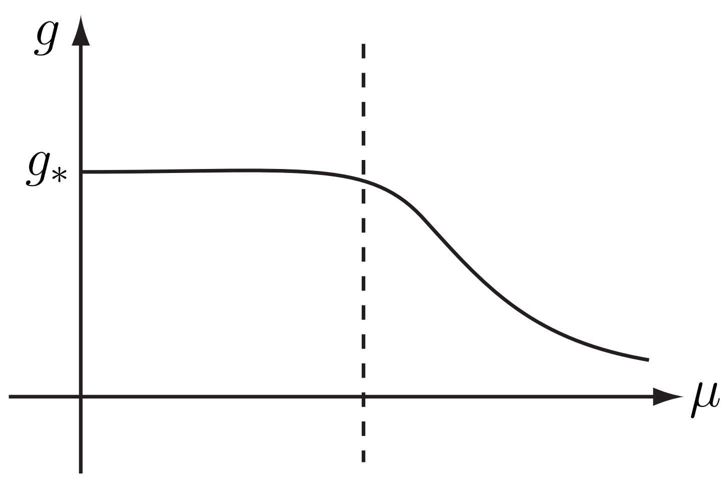
# Conformal Fixed Point

β function in QCD with $N_c$ colors and $N_f$ flavors:




$N_f \sim 1$

$\Rightarrow$ confining




$N_f \simeq \frac{11}{2} N_c$

$\Rightarrow$ conformal

Under active study by lattice community

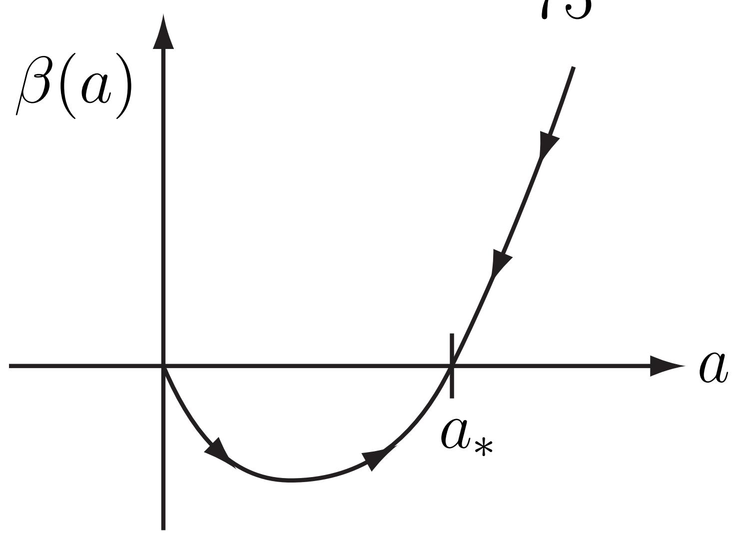
# Conformal Window

$a = \frac{N_c g^2}{16\pi^2} =$ perturbative expansion parameter

$x = \frac{N_f}{N_c} = \frac{11}{2} - \epsilon$ continuous for large $N_c, N_f$

$$\beta(a) \simeq -3\epsilon a^2 + \frac{3}{4}(75 - 26\epsilon)a^3 + \cdots$$

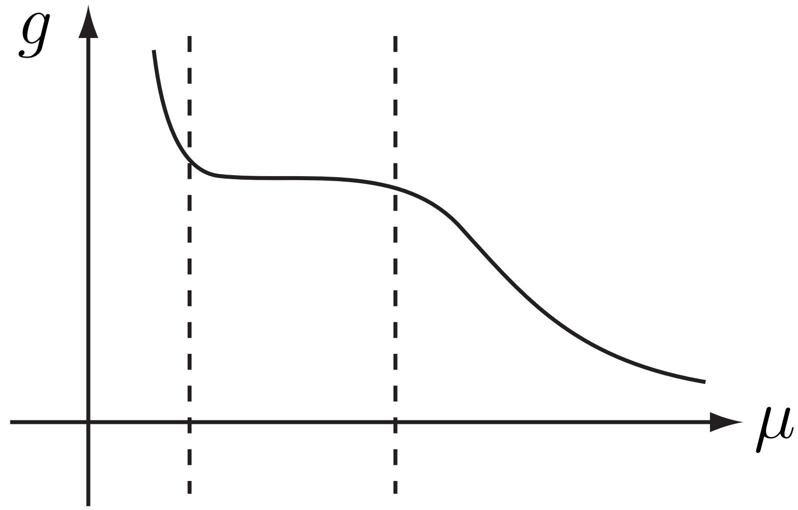
⇒ perturbative fixed point at $a_* = \frac{4\epsilon}{75}$ for $\epsilon \ll 1$




Expect "conformal window" for $x_c \leq x < \frac{11}{2}$

Lattice studies suggest $x_c \simeq 4$

# Conformal Breaking




- Walking technicolor (Holdom 1985; Appelquist, Karabali, Wijewardhana 1986; Yamawaki, Bando, Matumoto 1986)

  It "just does it"

  Plausible at $x = x_c$

- Conformal technicolor: "forced out" (ML, Okui 2004)

  $\Delta\mathcal{L} = -m\bar{\chi}\chi \qquad \chi =$ sterile technifermion

  Soft breaking of spacetime symmetry triggers electroweak symmetry breaking (c.f. SUSY)

# Status of Flavor?

$$\Lambda_t \sim \text{TeV}\left(\frac{\text{TeV}}{m_t}\right)^{1/(d-1)} \sim \begin{cases} 3\ \text{TeV} & \dim(H) = 3 \\ 10\ \text{TeV} & \dim(H) = 2 \\ 50\ \text{TeV} & \dim(H) = 1.5 \end{cases}$$

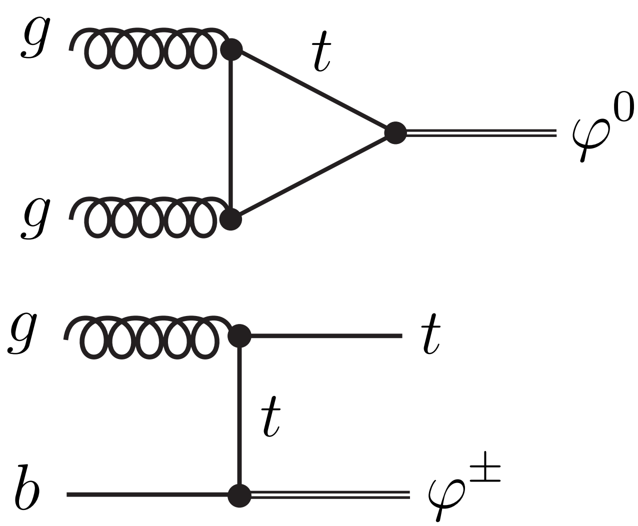
Still wanted: a complete theory of flavor without large flavor-changing neutral currents

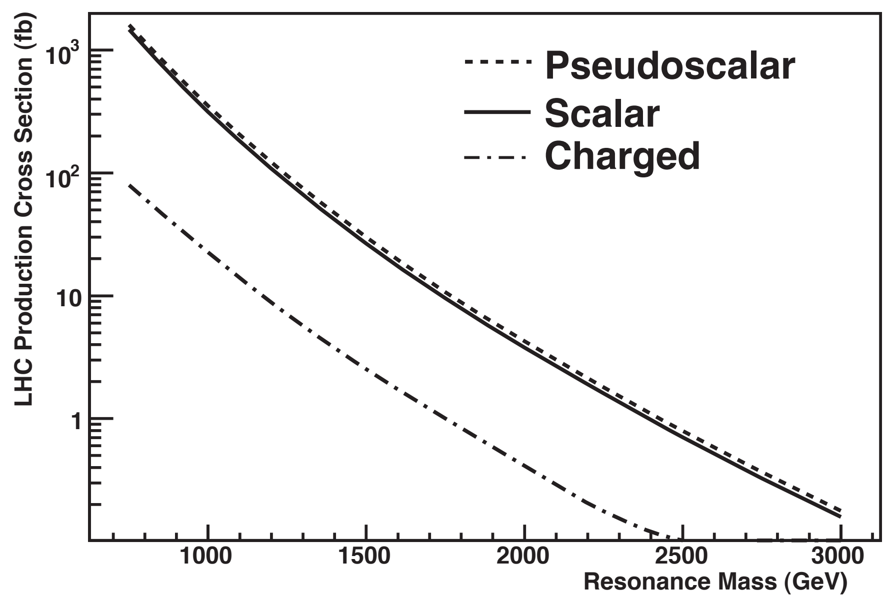
Complete theory still lacking
(Something I'm working on...)

# More Signals

$$\mathcal{L}_{\text{eff}} = \frac{1}{\Lambda_t^{d-1}} \bar{Q}_L H t_R + \cdots$$

⇒ production of strong resonances: $J = 0,\ CP = \pm,\ I = 0, 1$




$\varphi \to WW$ suppressed for $I = 1$ ⇒ can be narrow

Many interesting signals:

$$\varphi^0 \to \bar{t}t,\ W^+W^-Z,\ ZZZ, \ldots \qquad \varphi^+ \to \bar{b}t,\ W^+W^+W^-,\ W^+ZZ, \ldots$$

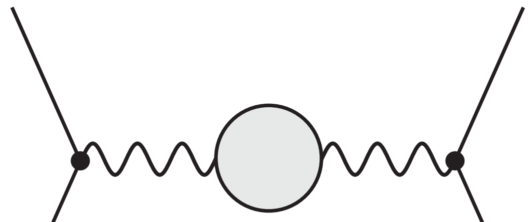
(Evans, ML 2009)

# Precision Electroweak

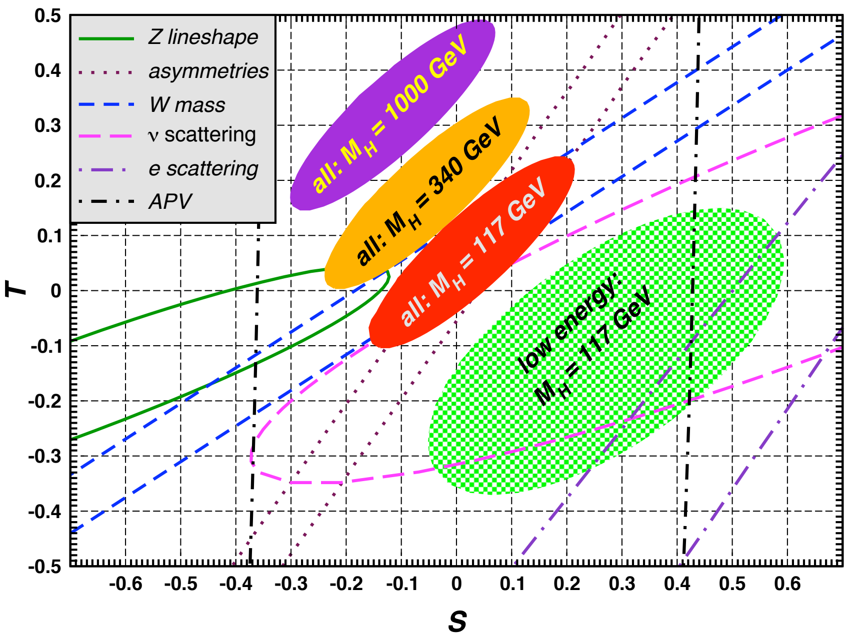
Effective theory below TeV contains gauge-violating terms

$$\Delta\mathcal{L}_{\text{eff}} = \tfrac{1}{2}\Delta M^2 W_3^{\mu} W_{3\mu} - \tfrac{1}{2}\epsilon W_3^{\mu\nu} B_{\mu\nu} + \cdots$$

$\Rightarrow$ leading corrections to



$\gamma, W, Z$

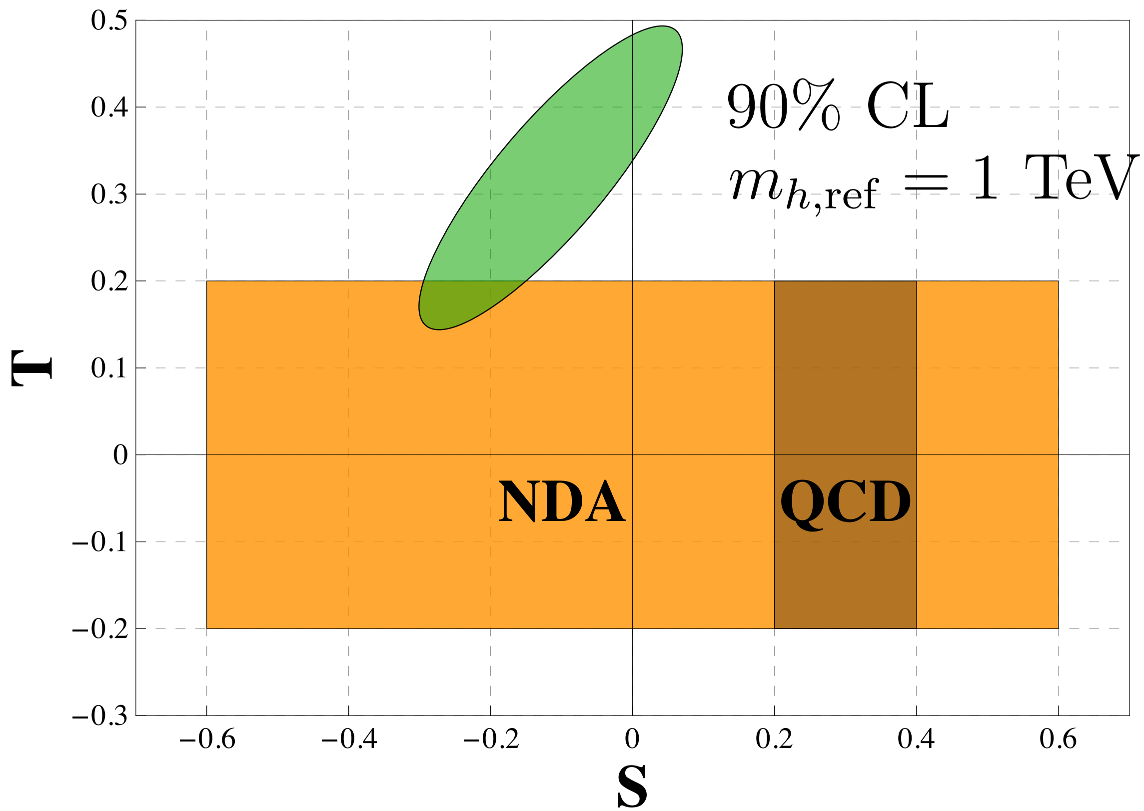



Erler, Langacker 2010

$$\rho,\, T \propto \Delta M^2$$

$$S \propto \epsilon$$

# Strong Higgs Sector




QCD: assume scaled-up QCD dynamics, use QCD data

NDA: all interactions $\rightarrow$ strong at TeV

No reliable prediction for walking/conformal theories

Not ruled out!

# Summary

危機

Mandarin: crisis = danger + opportunity

- A compelling solution to the naturalness problem

  $\dim(H^\dagger H) \geq 4$

- Top quark

  $\dim(H) < 3\,?$ Topcolor?

- Flavor and precision electroweak do not rule it out

- Distinctive signals at LHC

# Experiment will Decide...