Near Conformal Technicolor

Francesco Sannino

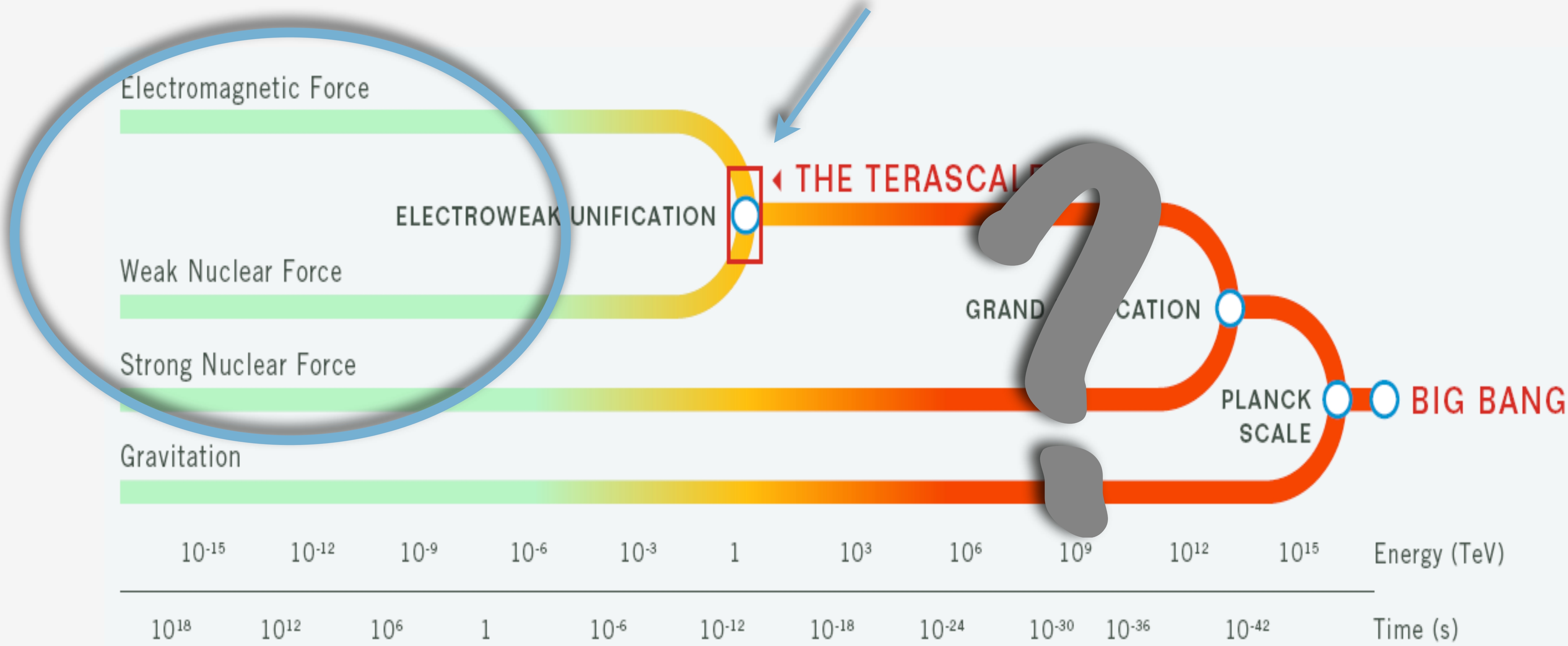
LNF 2008

F.S. - 0804.0182

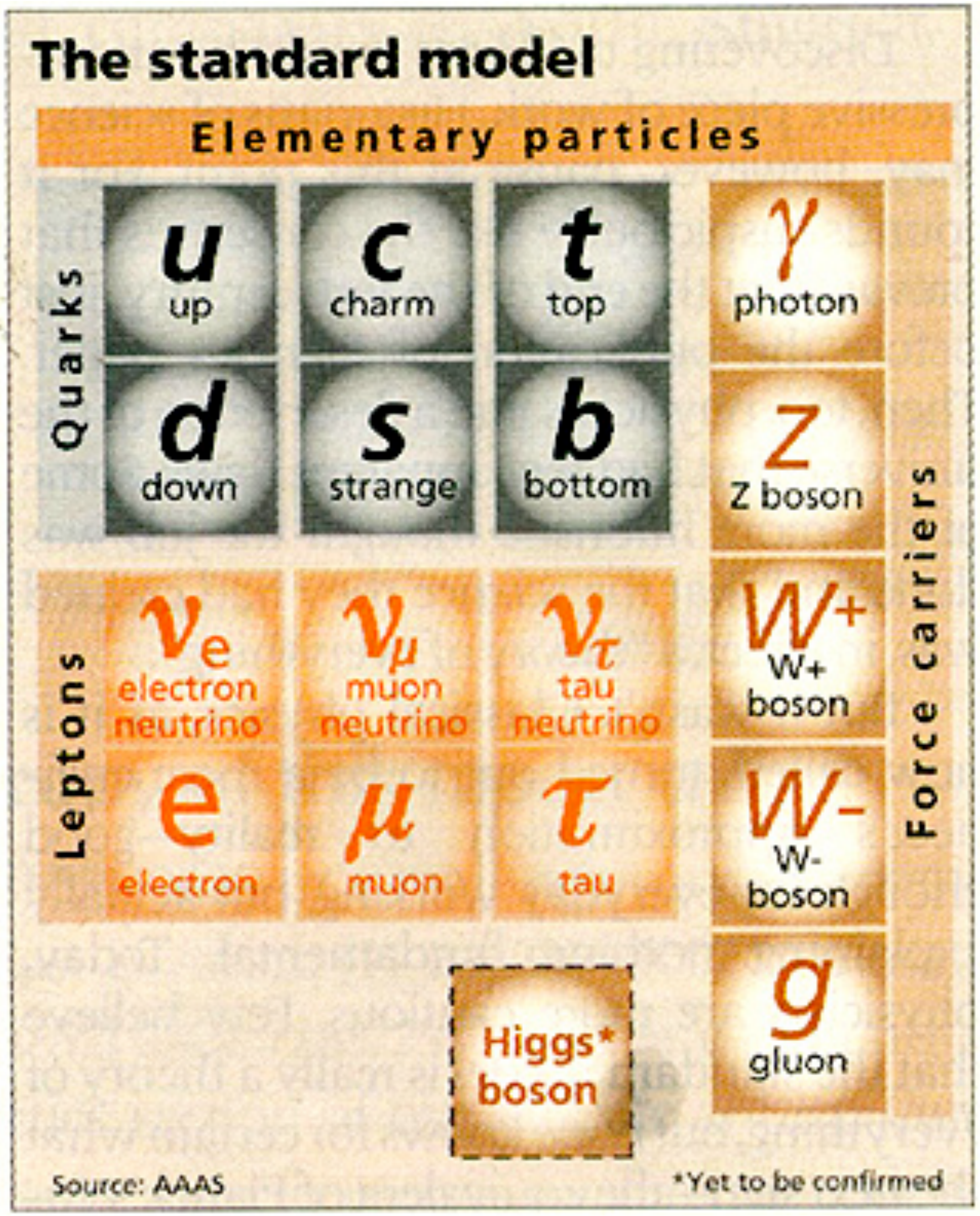
Where are we?

Standard Model

Fermi Scale



The SM on a post stamp



U(1)

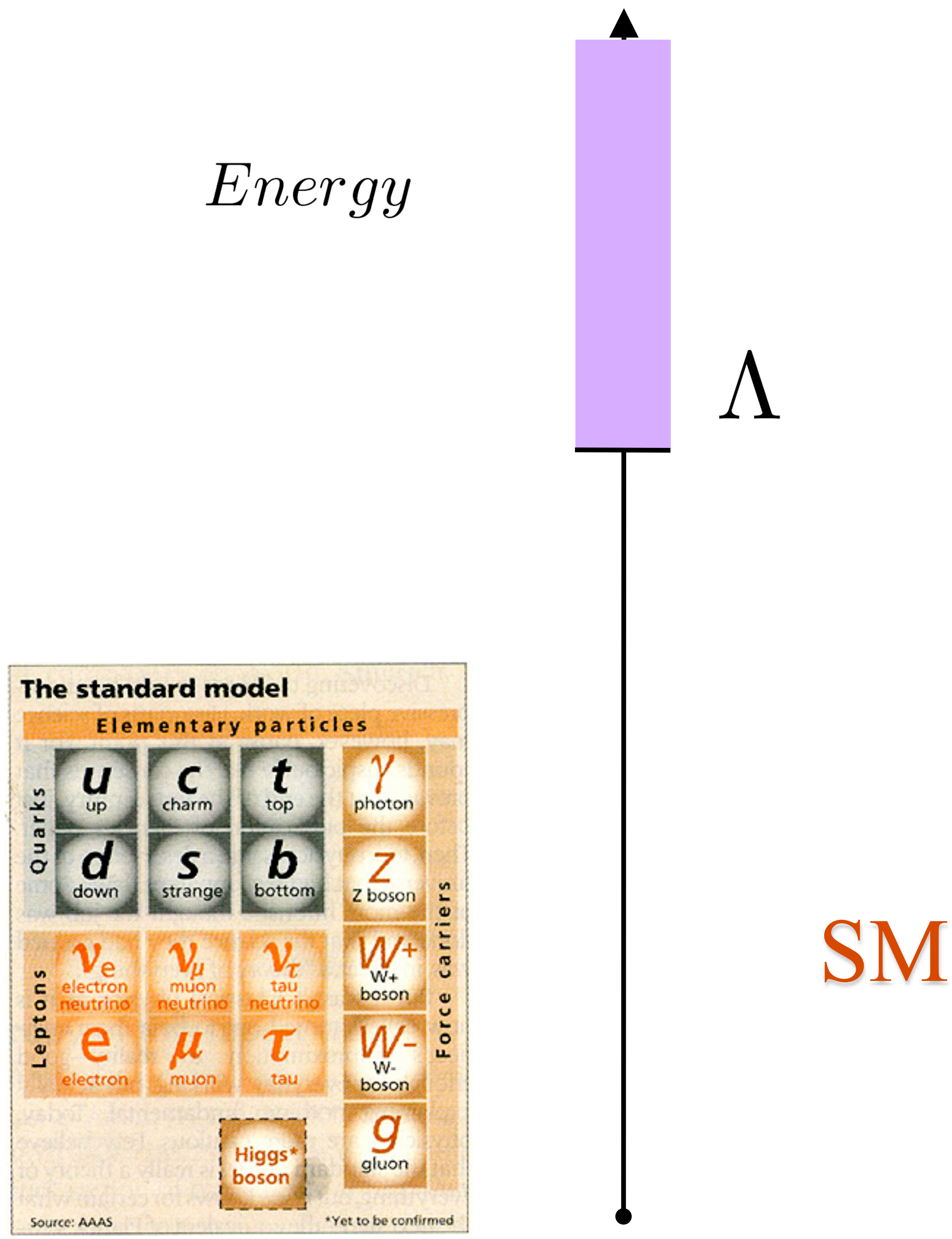
SU(2)

SU(3)

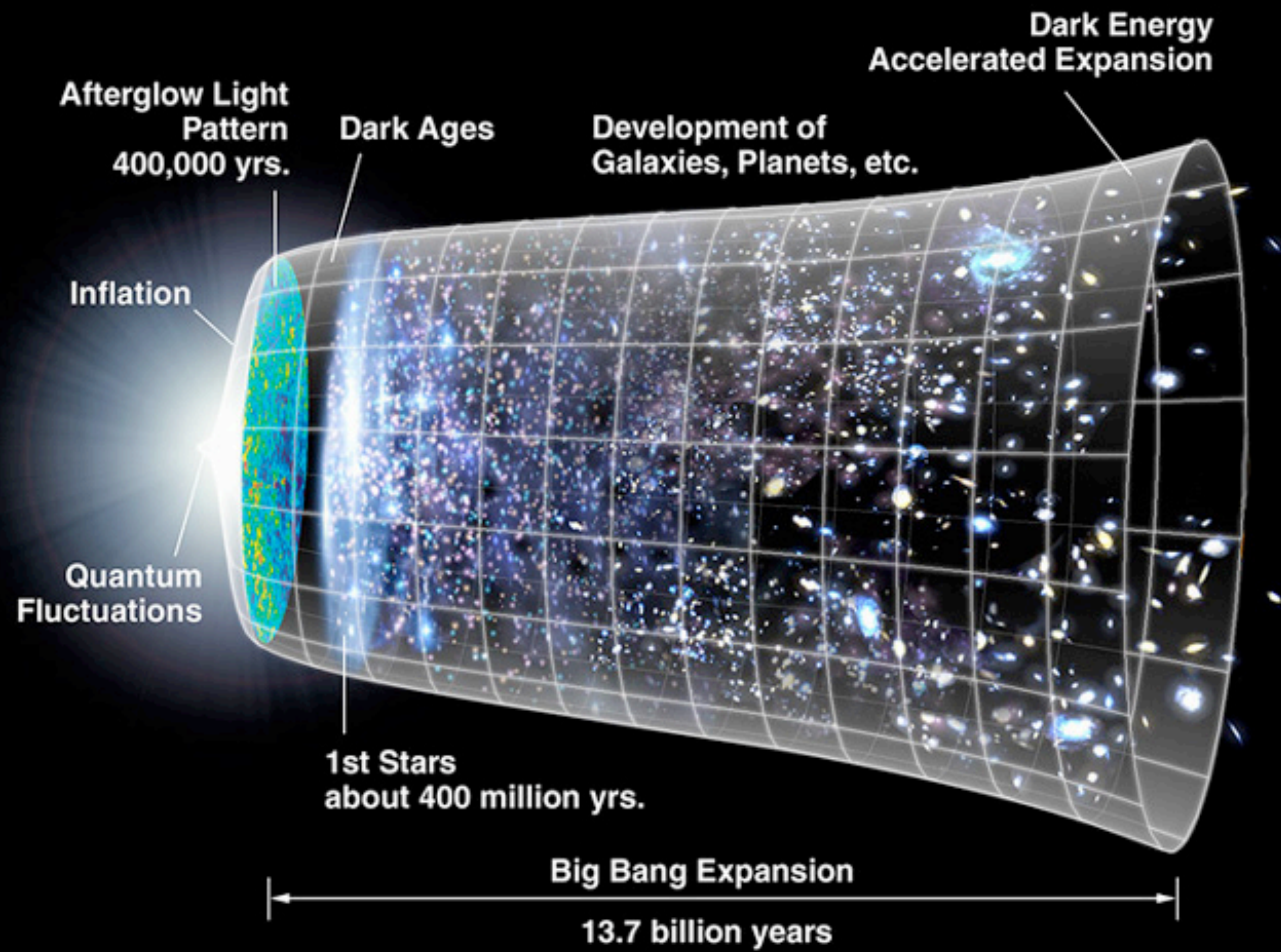
Simple Group Theoretical Structure

What is the Standard Model?

Low Energy Effective Theory



New Challenges from Cosmology

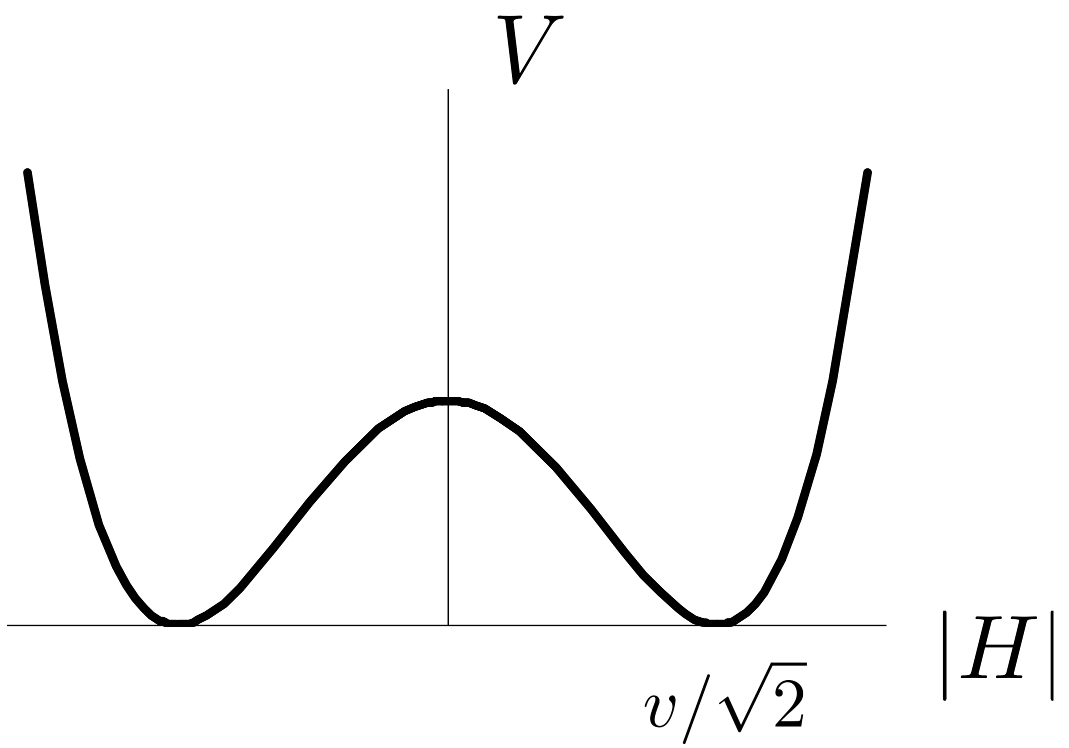

Dark Energy
Accelerated Expansion
Afterglow Light
Pattern
400,000 yrs.
Dark Ages
Development of
Galaxies, Planets, etc.
Inflation
Quantum
Fluctuations
1st Stars
about 400 million yrs.
Big Bang Expansion
13.7 billion years

- 4 % is Ordinary Matter
- 22% is Dark Matter
- 74 % is Pure Energy

Let there be Mass

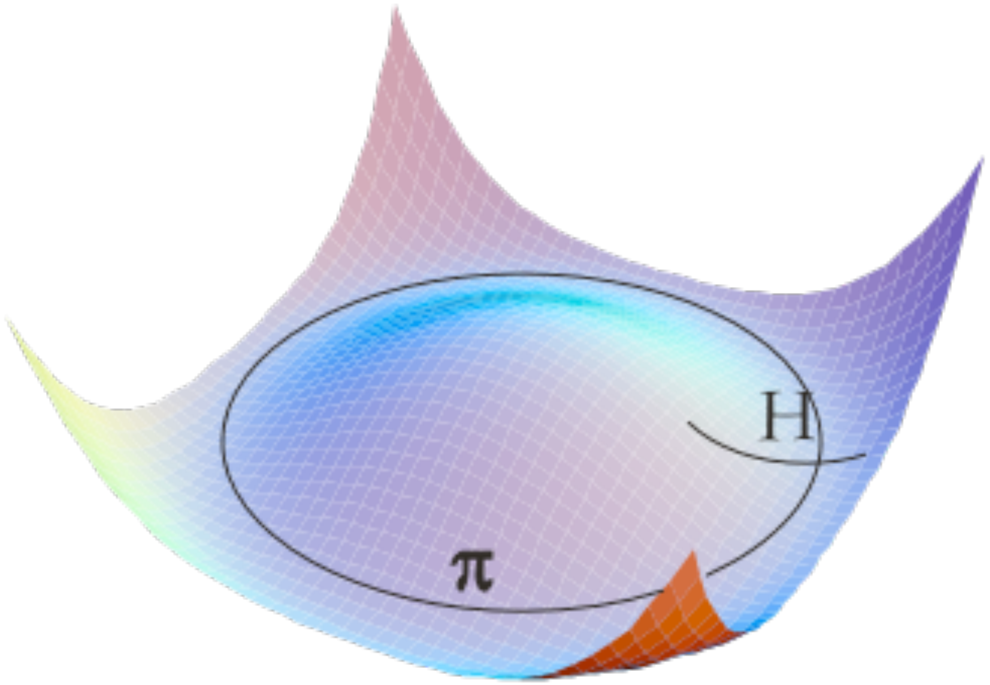
Higgs Mechanism in SM

$$m^2 < 0$$

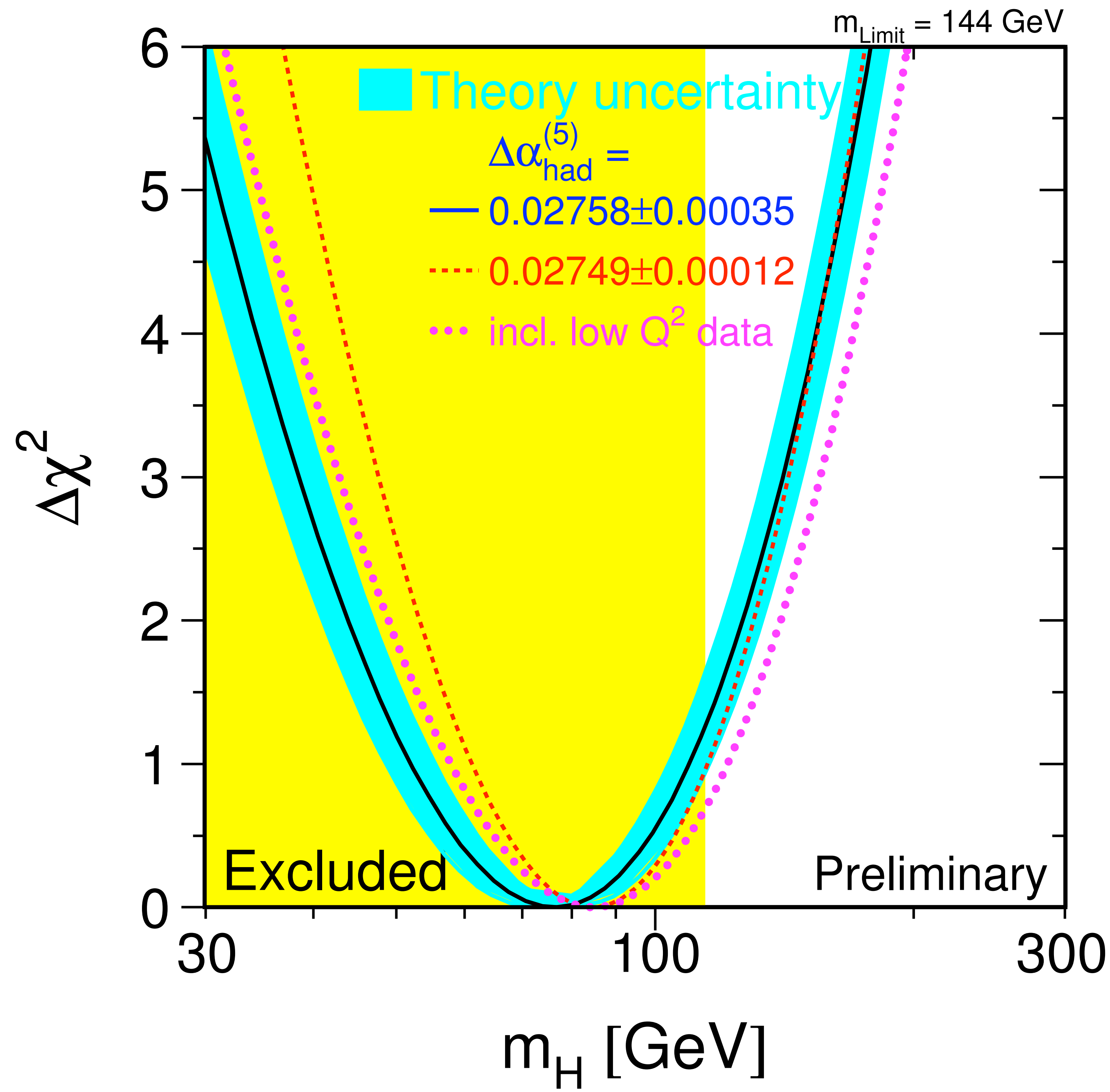


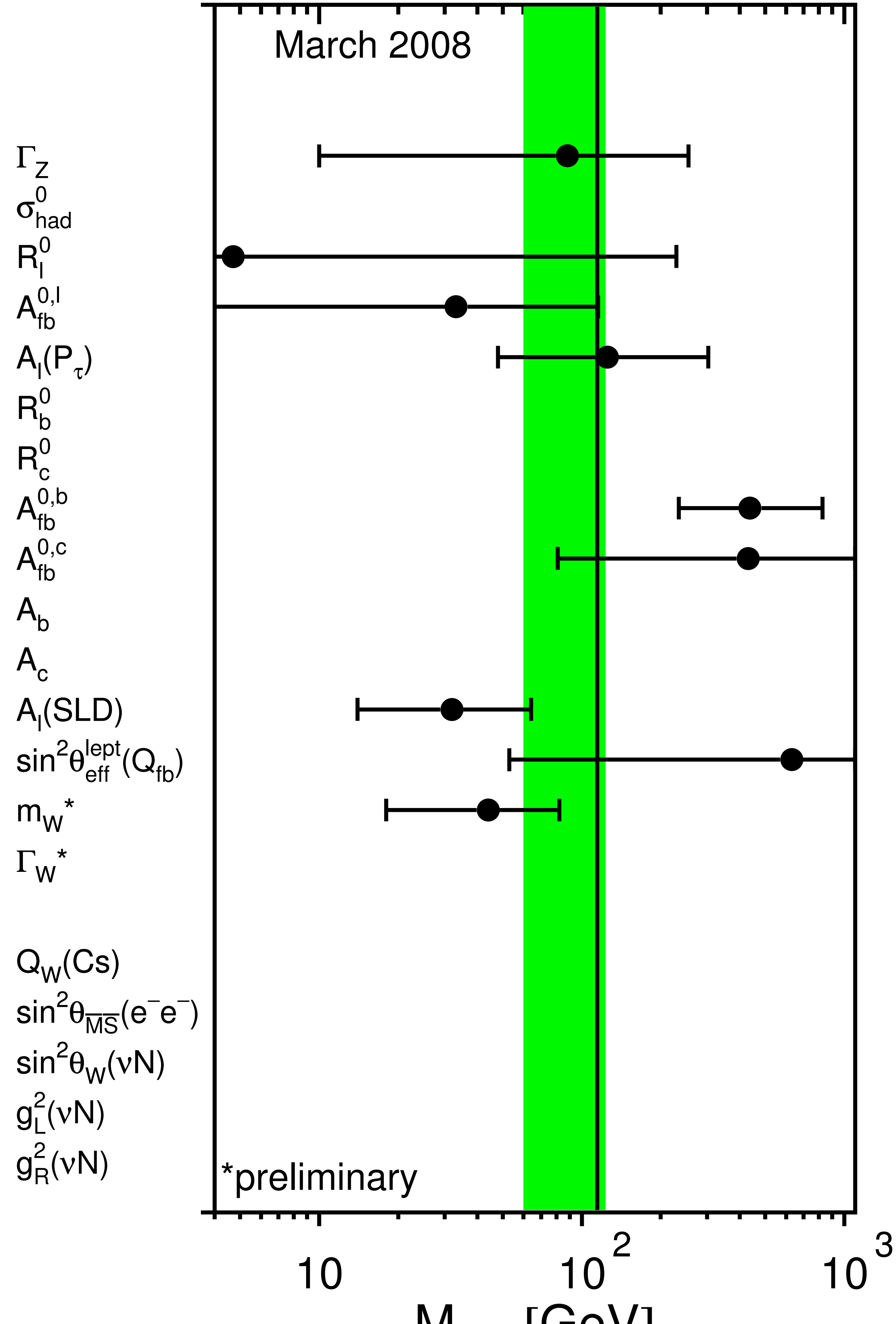
$$\langle \sigma^2 \rangle \equiv v^2 = \frac{|m^2|}{\lambda}$$

$$\sigma = v + h$$

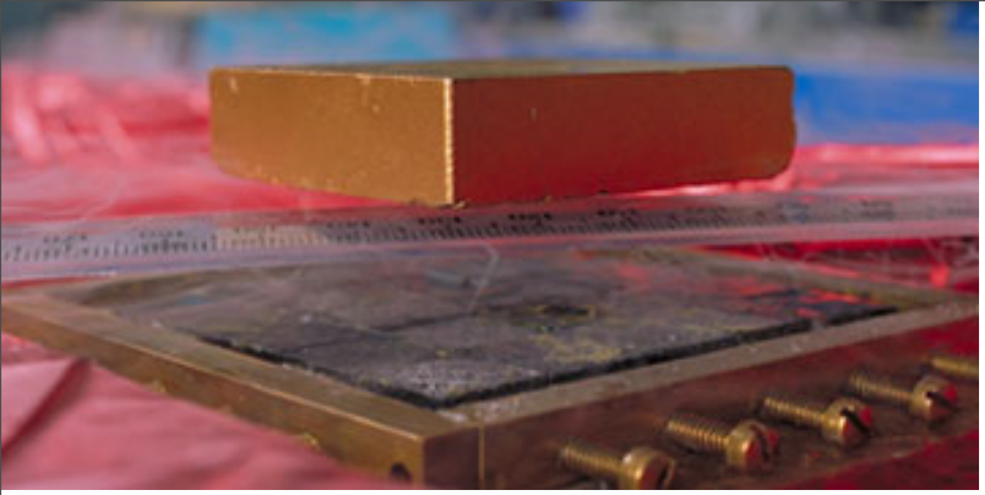


SM Higgs: Current Status:




March 2008
Γ_Z
σ^0_{had}
R^0_l
$A^{0,l}_{fb}$
$A_l(P_\tau)$
R^0_b
R^0_c
$A^{0,b}_{fb}$
$A^{0,c}_{fb}$
A_b
A_c
A_l(SLD)
$\sin^2\theta^{lept}_{eff}(Q_{fb})$
m_W*
Γ_W*
Q_W(Cs)
$\sin^2\theta_{\overline{MS}}(e^-e^-)$
$\sin^2\theta_W(\nu N)$
$g^2_L(\nu N)$
$g^2_R(\nu N)$
*preliminary
10
10^2
10^3
M_H [GeV]

Higgs Mechanism in Nature



Superconductivity

Macroscopic-Screening
Non-Relativistic

SM-Screening
Relativistic

$$T < T_c$$

$n_s = \text{Density SC electrons}$

$$|\psi|^2 = n_C = \frac{n_s}{2}$$

$$|H|^2 = \frac{v^2}{2}$$

Meissner-Mass

Static Vector Potential

$$M^2 = q^2 n_s/2m$$

$$m = 2m_e \quad q = -2e$$

$$n_s \sim 4 \times 10^{28} m^{-3}$$

$$\xi = 1/M \sim 10^{-6} cm$$

Hidden structure

Weak-GB-Mass

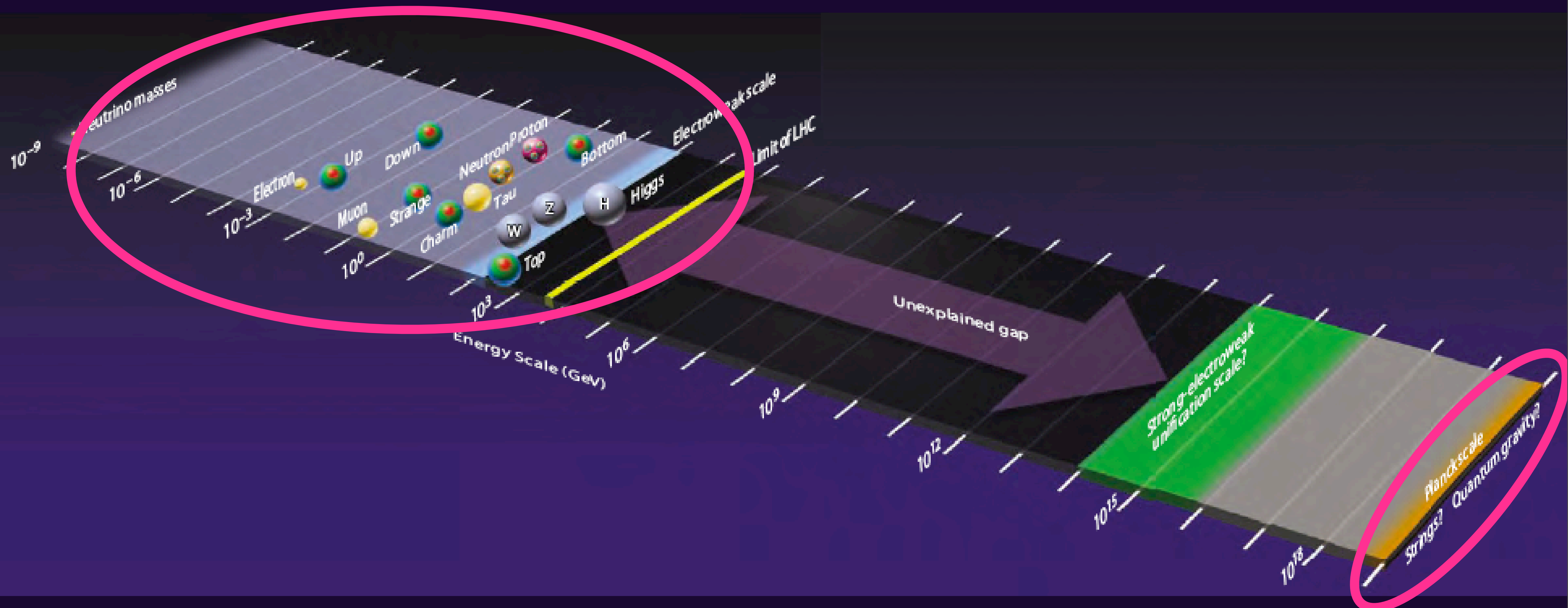
$$M_W^2 = g^2 v^2/4$$

$$M_W \sim 80\ GeV$$

$$\xi_W = 1/M_W \sim 10^{-15} cm$$

????

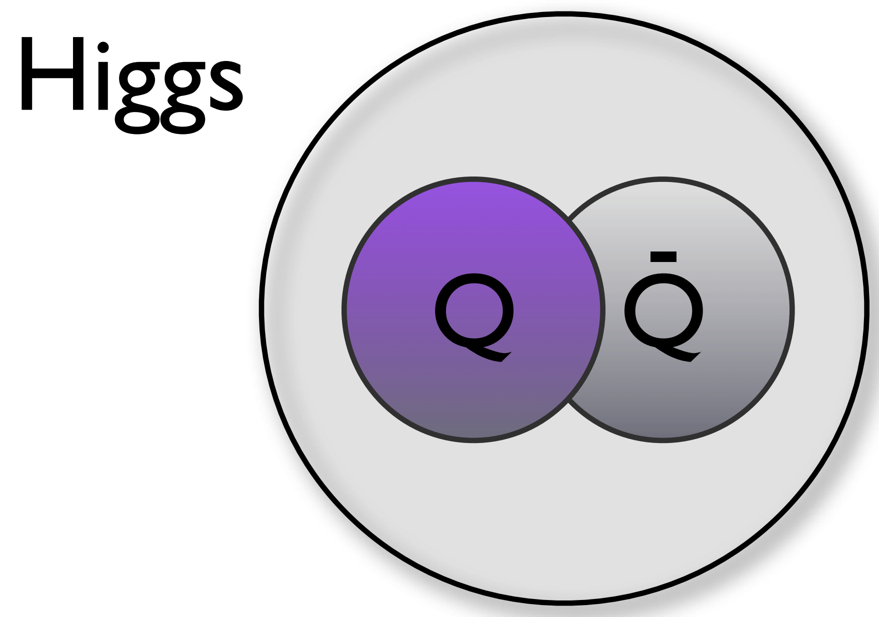
Instability of the Fermi Scale



Neutrino masses
Electron
Up
Down
Muon
Strange
Charm
Neutron/Proton
Tau
Bottom
W
Z
H
Higgs
Top
Electroweak scale
Limit of LHC
Unexplained gap
Strong-electroweak unification scale?
Planck scale
Strings?
Quantum gravity?
10^{-9}
10^{-6}
10^{-3}
10^{0}
10^{3}
10^{6}
10^{9}
10^{12}
10^{15}
10^{18}
Energy Scale (GeV)

Dynamical Stabilization

The Higgs is Composite of Fermions



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]

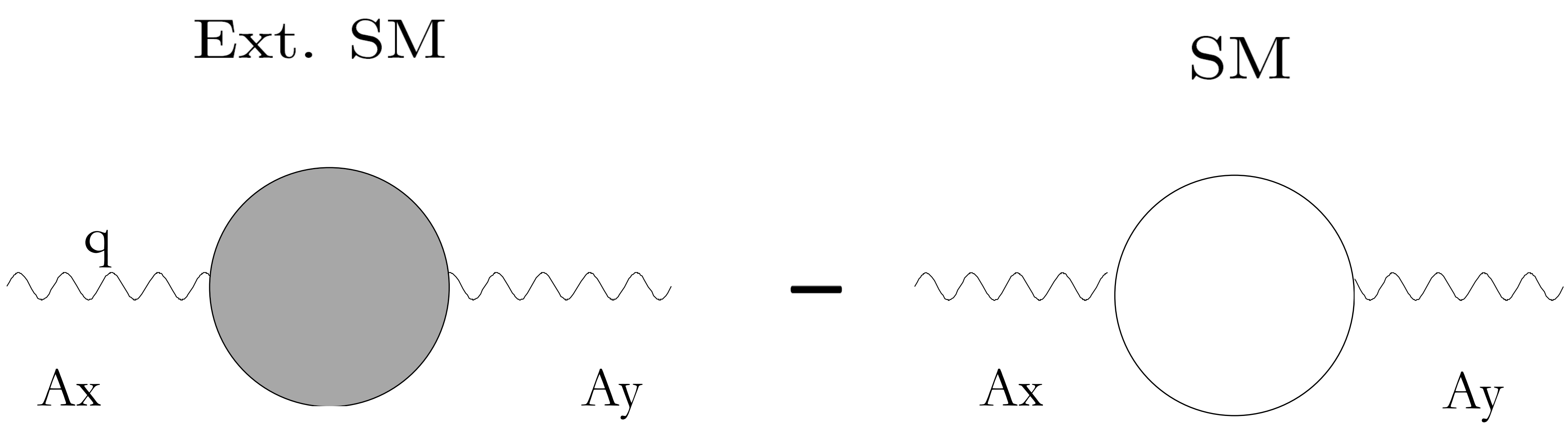
Natural to use QCD-like dynamics.

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

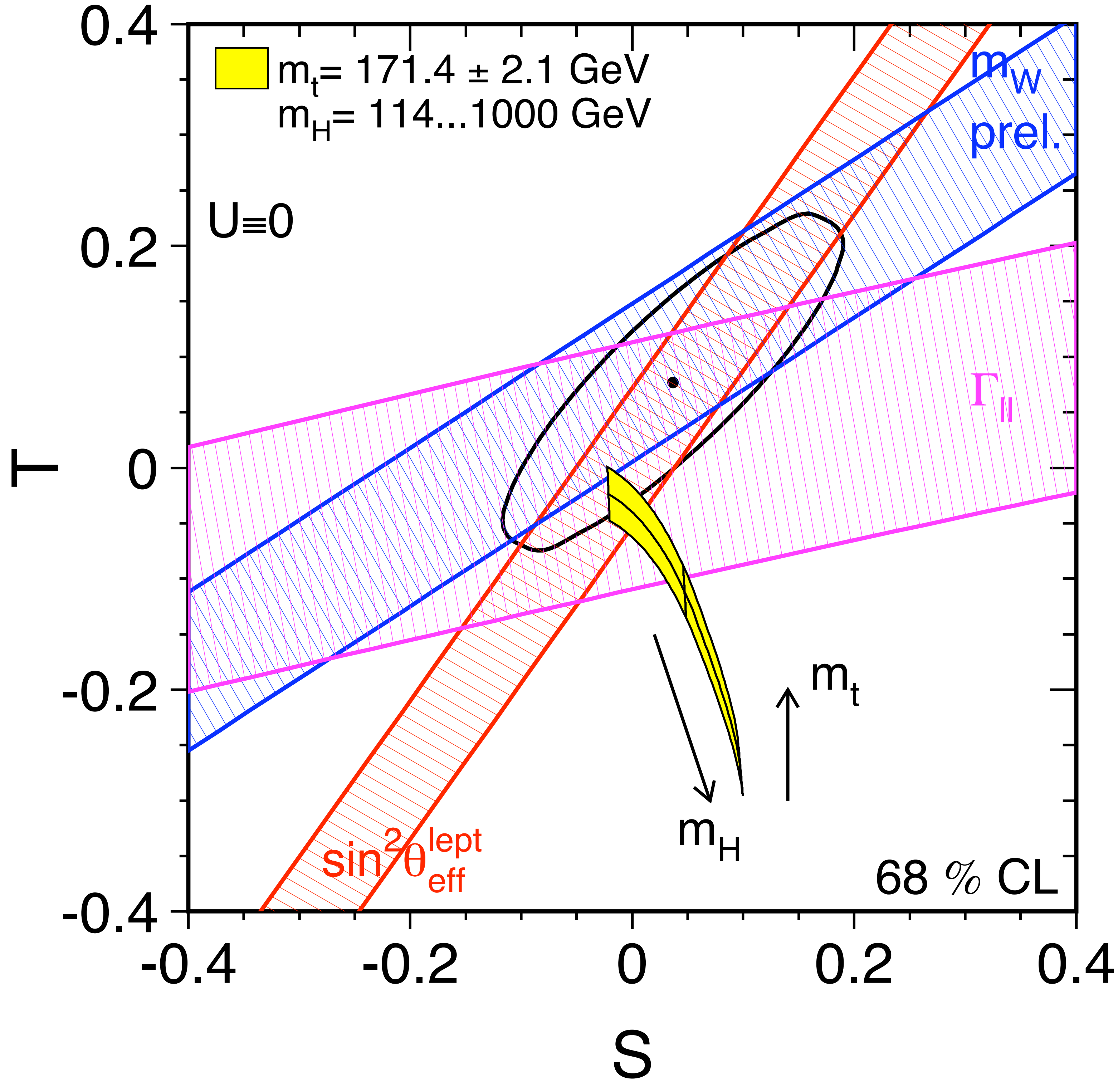
$$\langle Q^f \widetilde{Q}_{f'} \rangle = \Lambda_{TC}^3 \qquad \Lambda_{TC} \simeq 250 \; GeV$$

Electroweak Precision Measurements

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



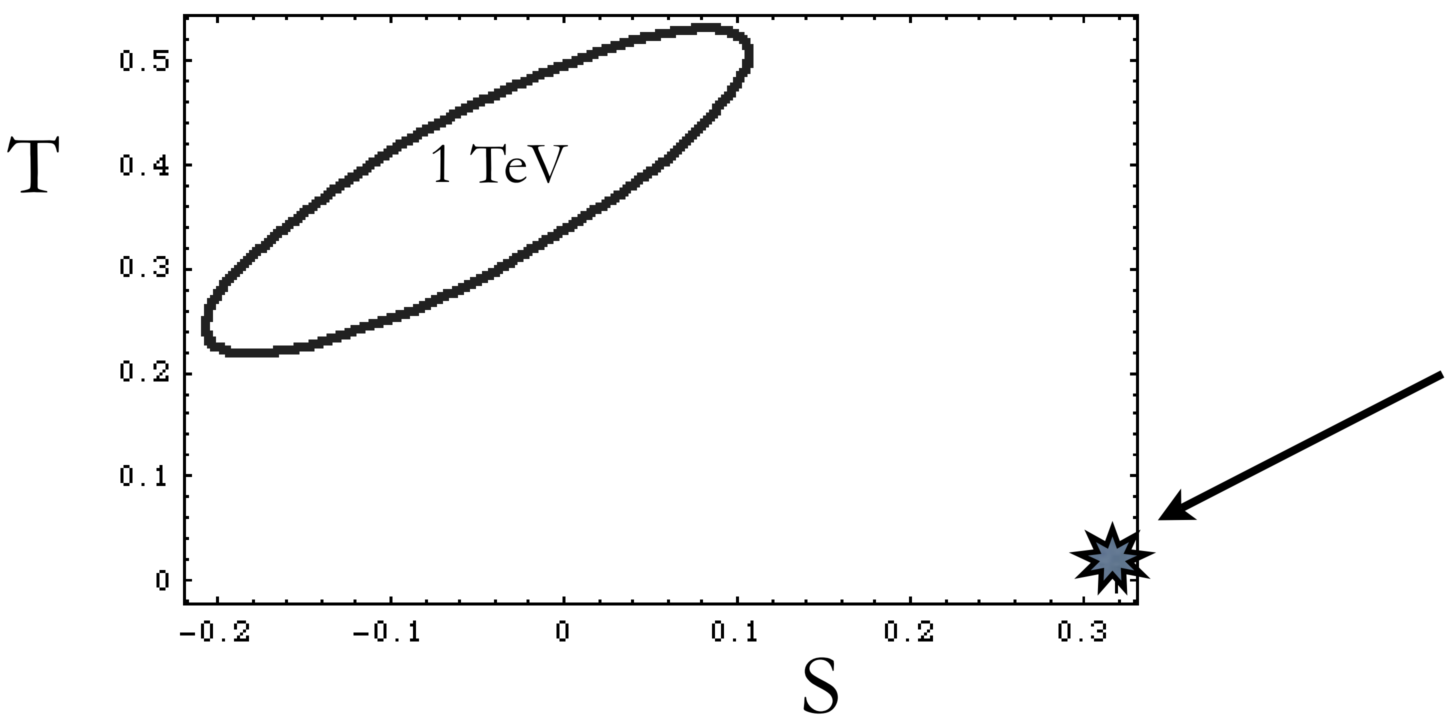
$$\Pi^{\mu\nu}_{XY}(q^2) = \Pi_{XY}(q^2) g^{\mu\nu} + \cdots$$



LEP EWG Summer 2006

Large & Positive S from QCD-like TC

Peskin and Takeuchi, 90



SU(3) + 1 Fundamental Doublet

Masses to SM Fermions

The need to Extend Technicolor

$$\bar{L} \cdot H e_R \qquad \rightarrow \qquad \bar{L} \frac{\bar{Q}Q}{\Lambda_{ETC}^2} e_R$$

Different Approaches

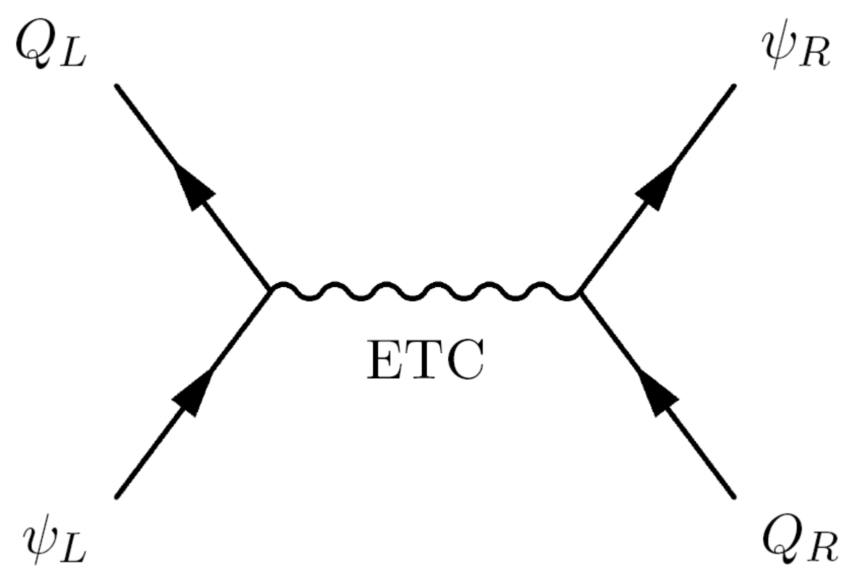
Scalar-less New Gauge Interactions (Extended TC)

Marry SUSY and Technicolor

Add New Scalars in the Flavor Sector

.....

Extended Technicolor



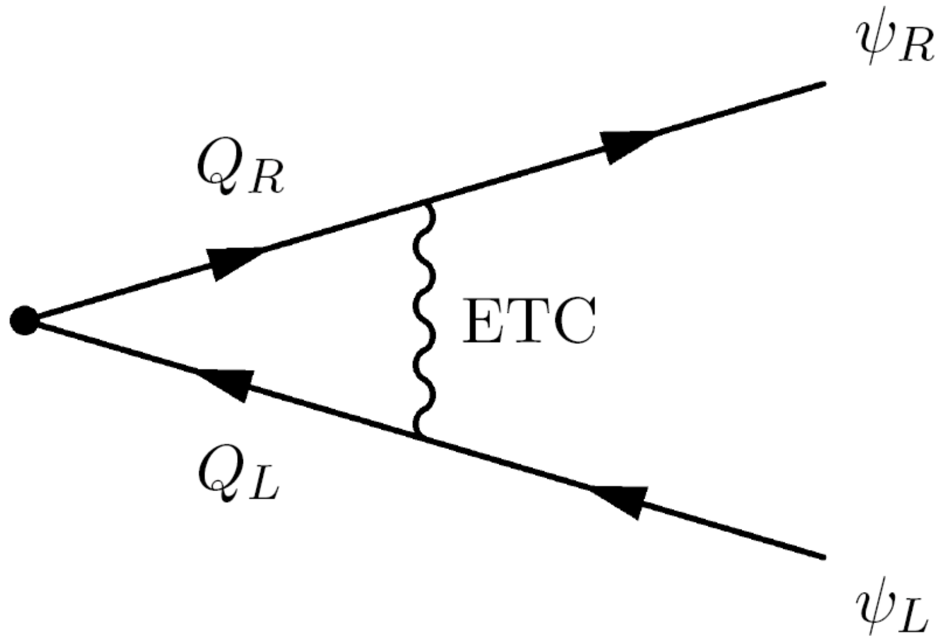
$$\alpha_{ab}\frac{\bar{Q}T^aQ\bar{Q}T^bQ}{\Lambda^2_{ETC}}+\beta_{ab}\frac{\bar{Q}_LT^aQ_R\bar{\psi}_RT^b\psi_L}{\Lambda^2_{ETC}}+\gamma_{ab}\frac{\bar{\psi}_LT^a\psi_R\bar{\psi}_RT^b\psi_L}{\Lambda^2_{ETC}}+\ldots$$

PNG Masses

SM-Fermion Masses

FCNC Operators

Beta - Terms



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

Gamma - Terms

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

$$\downarrow$$

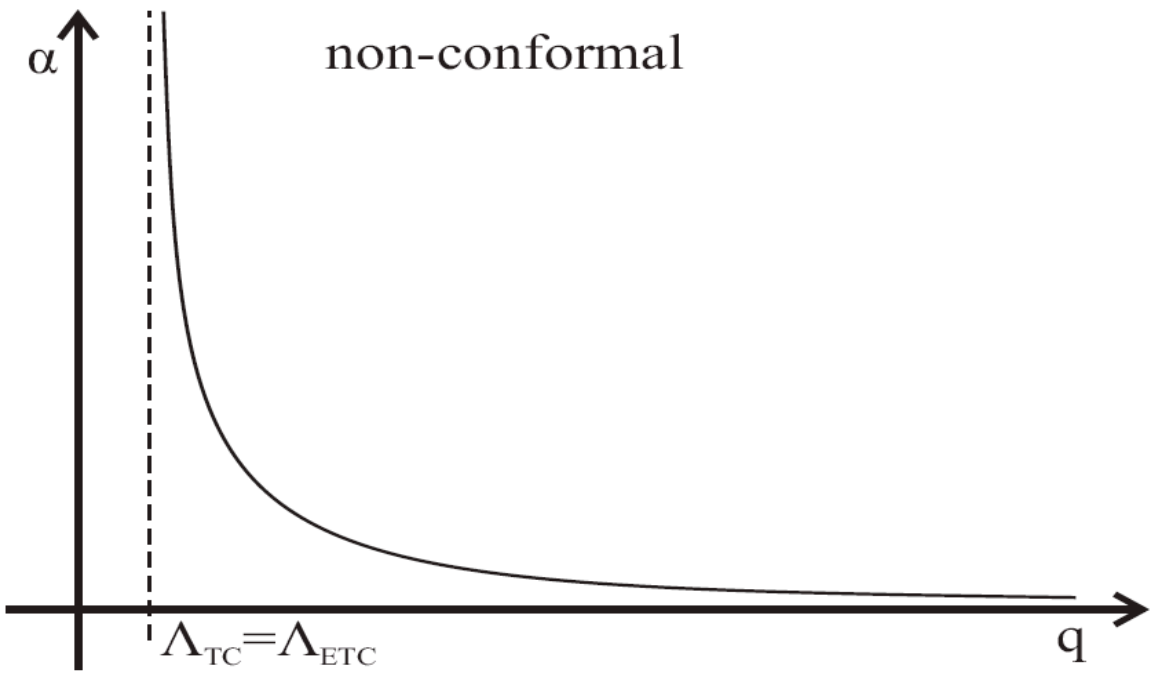
$$\Lambda_{ETC} \geq 10^3 \Lambda_{TC}$$

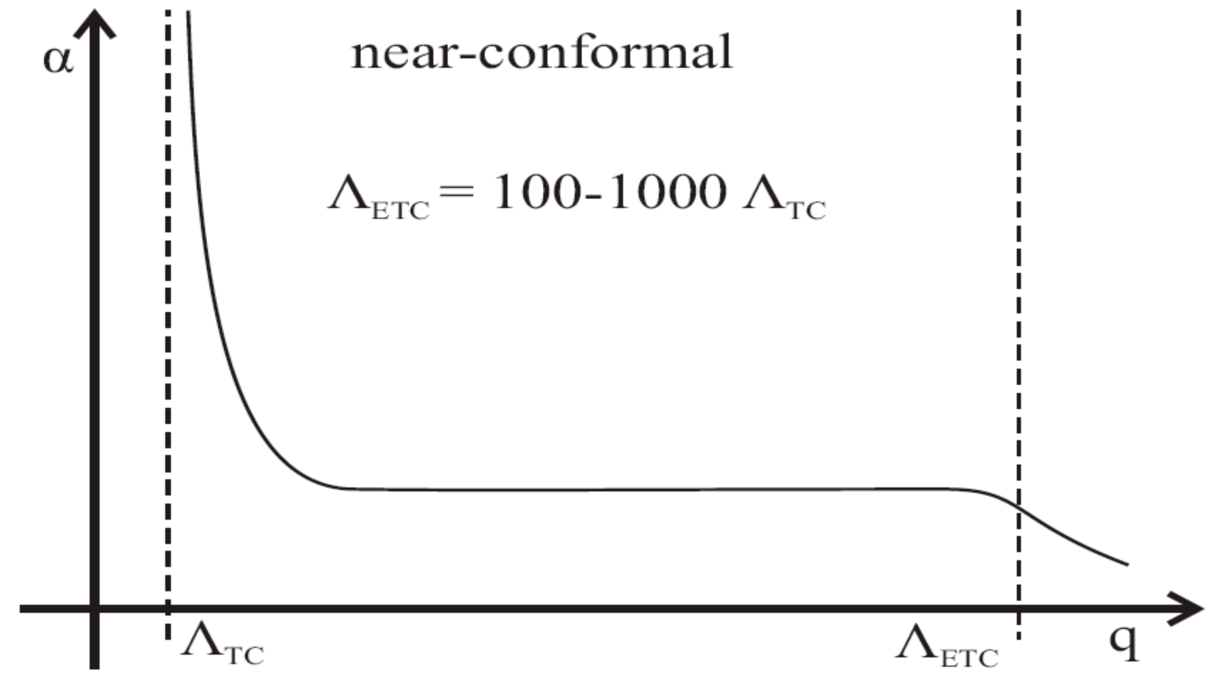
Too small Top mass if

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

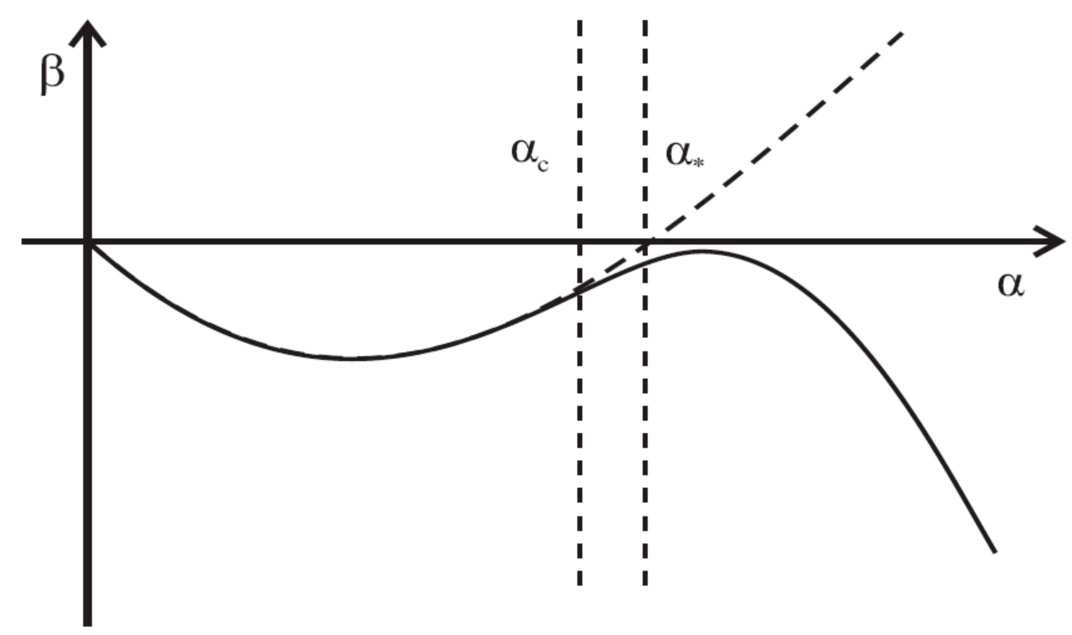
Walking versus Running

Near Conformal Properties





Holdom
Eichten and Lane



Why the walking can help ?

$$\langle \bar{Q}Q_{ETC} \rangle = \exp\left(\int_{\Lambda_{TC}}^{\Lambda_{ETC}} d\ln(\mu)\ \gamma_m(\alpha(\mu)) \right) \langle \bar{Q}Q_{TC} \rangle$$

QCD-Like

$$\exp\left(\int_{\Lambda_{TC}}^{\Lambda_{ETC}} d\ln(\mu)\ \gamma_m(\alpha(\mu)) \right) \quad \sim \quad (\ln(\Lambda_{ETC}/\Lambda_{TC}))^{\gamma_m}$$

Near the conformal window

$$\exp\left(\int_{\Lambda_{TC}}^{\Lambda_{ETC}} d\ln(\mu)\ \gamma_m(\alpha(\mu)) \right) \quad \sim \quad (\Lambda_{ETC}/\Lambda_{TC})^{\gamma_m(\alpha^\star)}$$

Fermion Mass Enhancement

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

S in Walking Technicolor

$$S_{\mathrm{pert}} = \frac{1}{6\pi}\frac{N_f}{2}d(R)$$

$$S_{WTC} < S_{TC}$$

Appelquist, F.S.

However we will take:

$$S_{WTC} \approx S_{\mathrm{pert}}$$

Besides

$$S = S_{(W)TC} + S_{NS}$$

Offset the first term

S from extra Leptons

$$\text{Fermions :} \qquad \psi_L = \begin{pmatrix} \psi_{1L} \\ \psi_{2L} \end{pmatrix}, \qquad \psi_{1R}\,, \qquad \psi_{2R}$$

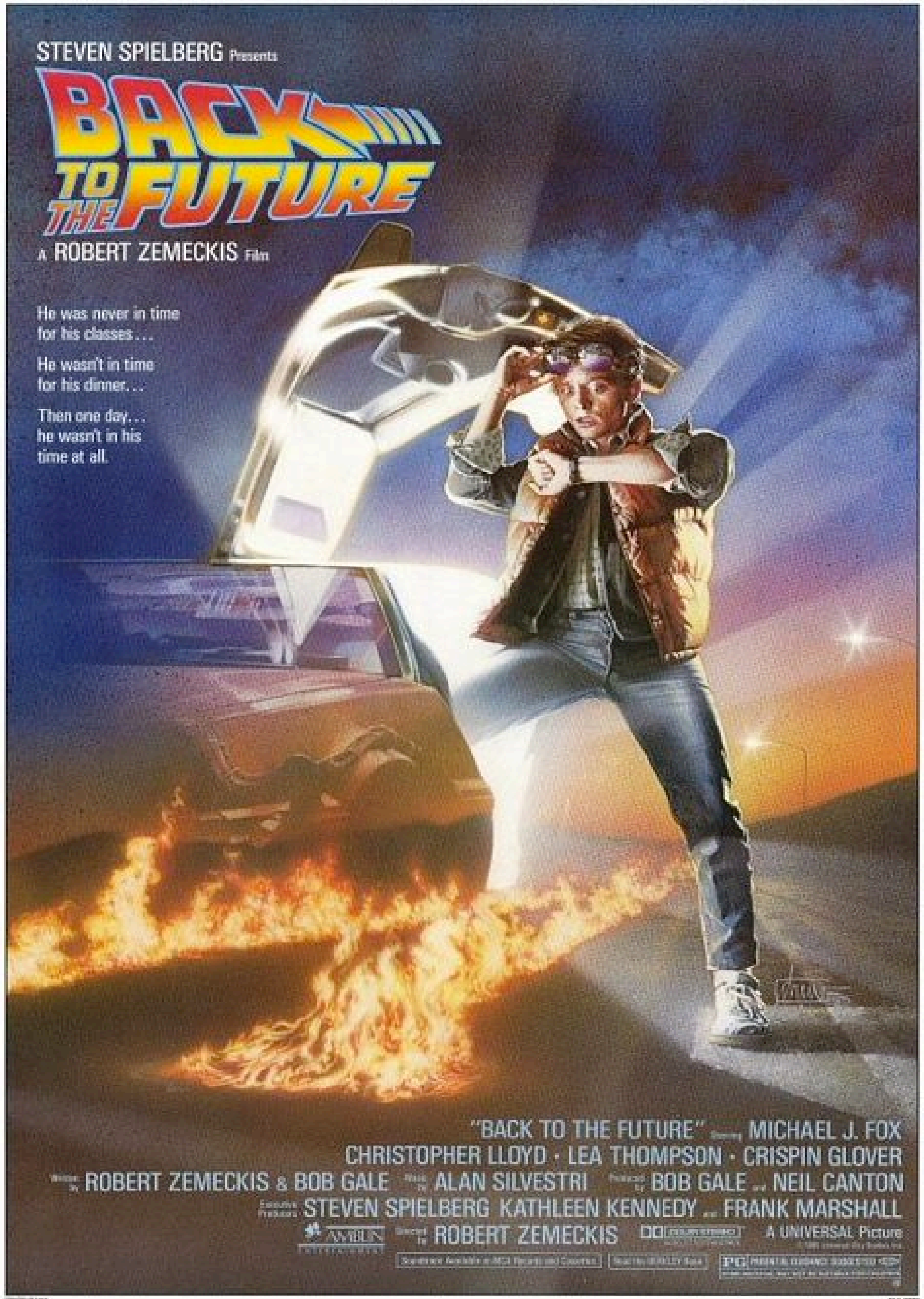
$$\text{Hypercharge :} \qquad Y\,, \qquad Y + \frac{1}{2}, \qquad Y - \frac{1}{2}$$

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

$$M_{1,2}^2 \gg m_Z^2$$

Rule:

Find Walking Theories with EW embedding minimizing S



STEVEN SPIELBERG Presents
BACK TO THE FUTURE
A ROBERT ZEMECKIS Film
He was never in time
for his classes...
He wasn't in time
for his dinner...
Then one day...
he wasn't in his
time at all.
"BACK TO THE FUTURE" MICHAEL J. FOX
CHRISTOPHER LLOYD · LEA THOMPSON · CRISPIN GLOVER
ROBERT ZEMECKIS & BOB GALE ALAN SILVESTRI BOB GALE NEIL CANTON
STEVEN SPIELBERG KATHLEEN KENNEDY FRANK MARSHALL
AMBLIN ROBERT ZEMECKIS
A UNIVERSAL Picture
PG

Use:

Near Conformal Dynamics (Walking Dynamics)

Phase Diagram for Gauge Theories

First Principle Lattice Computations

Identified Many EW Viable Walking and Custodial TC Models

Minimal Walking Technicolor (MWT)

Higher Dimensional Representations

F.S. - Tuominen 04
Dietrich - F.S. - Tuominen 05
Dietrich - F.S. 06

Beyond Minimal Walking Technicolor

Partially EW Gauged Technicolor = Conformal Technicolor — F.S. 08, Luty 08

Split Technicolor

Ultra Minimal Technicolor

Ryttov, F.S. To appear soon

Additional Fermions in SM

Gudnason, Ryttov, F.S. 06

Custodial TC

Similar to BESS models of
Casalbuoni et al.

Appelquist, F.S. 98
Foadi, Frandsen, F.S. 07

Dark Matter

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

What if DM is due to an asymmetry?

A particle similar to the nucleon

But electrically neutral

At most EW-type cross sections

Great if connected to the Electroweak Symmetry Breaking sector of the SM

Technicolor is a natural example

Technibarion is similar to the nucleon

TB number like the B number

At most EW-type cross sections

EW scale and interactions built in

Nussinov, 86
Barr - Chivukula - Farhi 90
Gudnason - Kouvaris - F.S. 06

Naive estimates

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

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

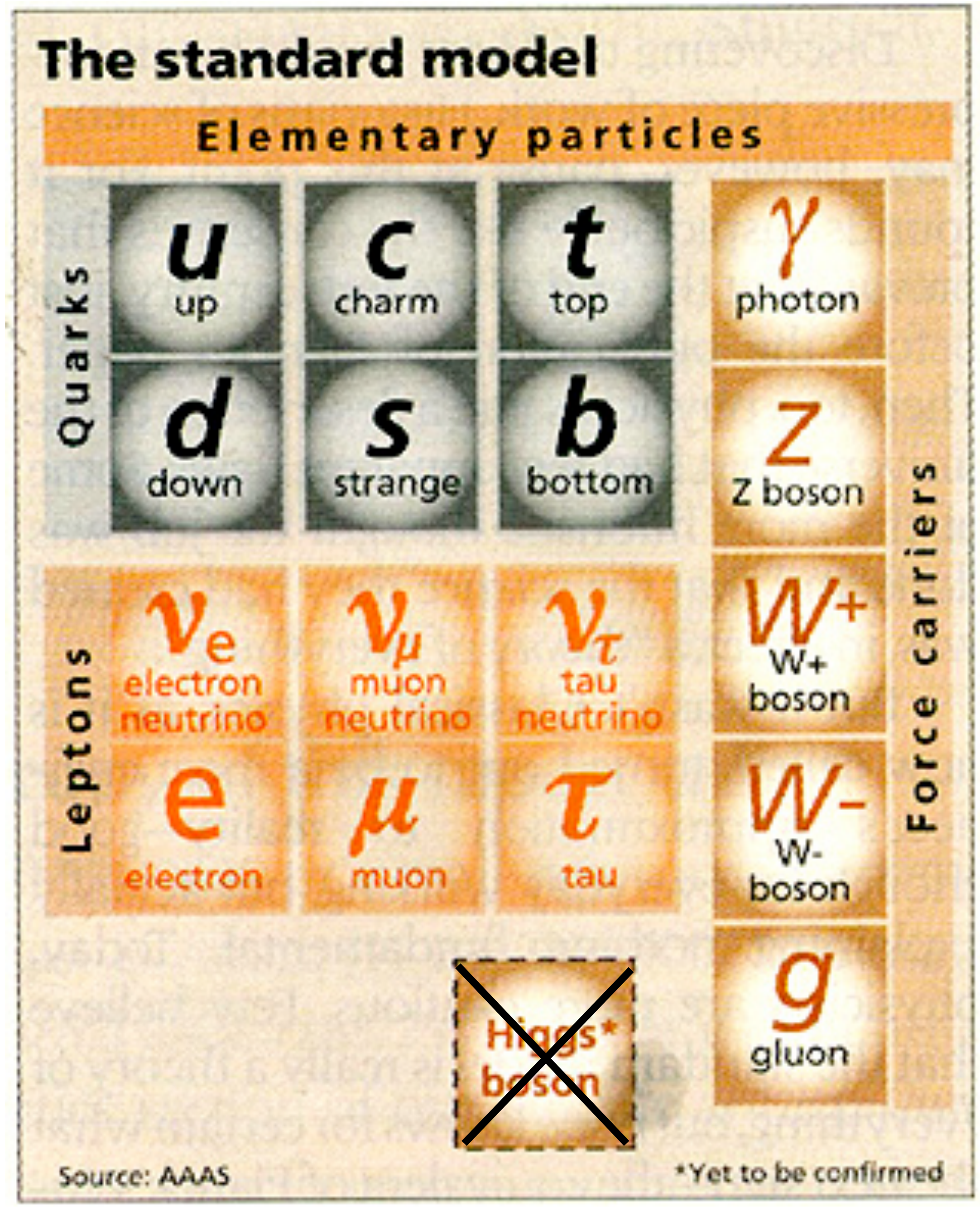
$$\frac{\Omega_{TB}}{\Omega_B} = \frac{TB}{B}\frac{m_{TB}}{m_p} \sim \mathcal{O}(1)$$

The Benchmark

Minimal Walking Technicolor

F.S. with Dietrich and Tuominen 05

Foadi, Frandsen, Ryttov, F.S. 07



U(1)

SU(2)

SU(3)

N
Extra Neutrino

E
Extra Electron

U
t-up

G
t-glue

D
t-down

SU(2)

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

The MWT Lagrangian

$$\mathcal{L}_H \rightarrow \boxed{-\frac{1}{4}\mathcal{F}^a_{\mu\nu}\mathcal{F}^{a\mu\nu} + i\bar{Q}_L\gamma^\mu D_\mu Q_L + i\bar{U}_R\gamma^\mu D_\mu U_R + i\bar{D}_R\gamma^\mu D_\mu D_R}$$
$$+ i\bar{L}_L\gamma^\mu D_\mu L_L + i\bar{N}_R\gamma^\mu D_\mu N_R + i\bar{E}_R\gamma^\mu D_\mu E_R$$

$$\mathcal{F}^a_{\mu\nu} = \partial_\mu \mathcal{A}^a_\nu - \partial_\nu \mathcal{A}^a_\mu + g_{TC}\epsilon^{abc}\mathcal{A}^b_\mu \mathcal{A}^c_\nu \qquad a, b, c = 1, \ldots, 3$$

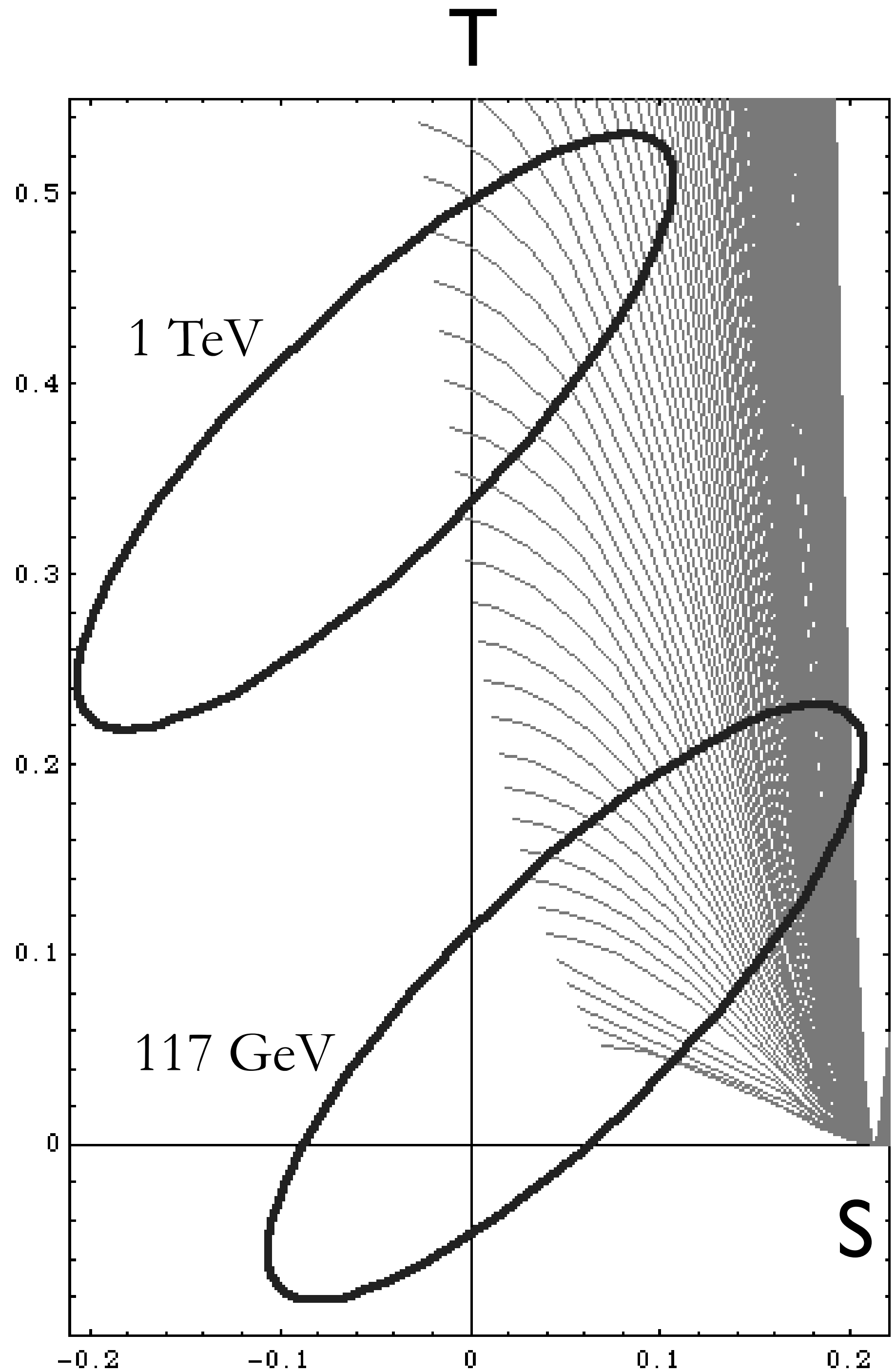
$$D_\mu Q^a_L = \left(\delta^{ac}\partial_\mu + g_{TC}\mathcal{A}^b_\mu \epsilon^{abc} - i\frac{g}{2}\vec{W}_\mu \cdot \vec{\tau}\delta^{ac} - ig'\frac{y}{2}B_\mu \delta^{ac}\right) Q^c_L$$

What you see is "not" what LHC will see

LHC effective theory

$$\boxed{\mathcal{L}(\mathrm{Composites}) + \mathcal{L}(\mathrm{Mixing\ with\ SM})} + \mathcal{L}(\mathrm{New\ Leptons}) + \mathcal{L}(\mathrm{SM-Higgs})$$

MWT versus EWPD



LEP EWG Summer 2006

$$46 \text{ Gev} < M_1 < 800 \text{ Gev}$$

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

Y=-1/2 for Leptons

Comprehensive Effective Technicolor Lagrangian

Vector Mesons

Yukawas

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

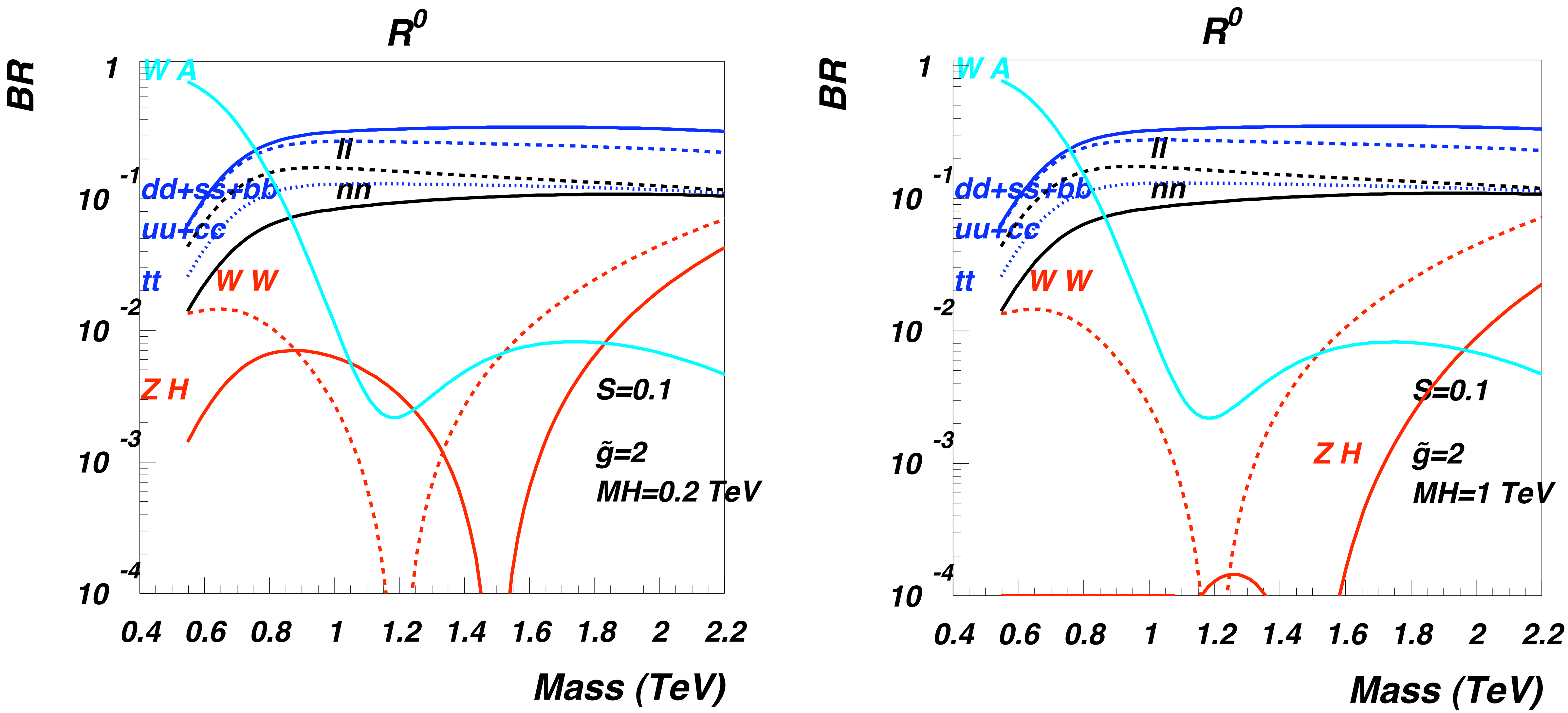
Written in a renormalizable form

With imposed constraints from Precision Data

<u>A working technicolor benchmark</u>

Foadi, Frandsen, Ryttov & F.S. 07

Vector Resonances Branching Ratios



BRs for different Composite Higgs Masses

BR in WW drops and rises (small S)

Unification

Farhi-Susskind, 79

Gudnason-Ryttov-F.S. 06

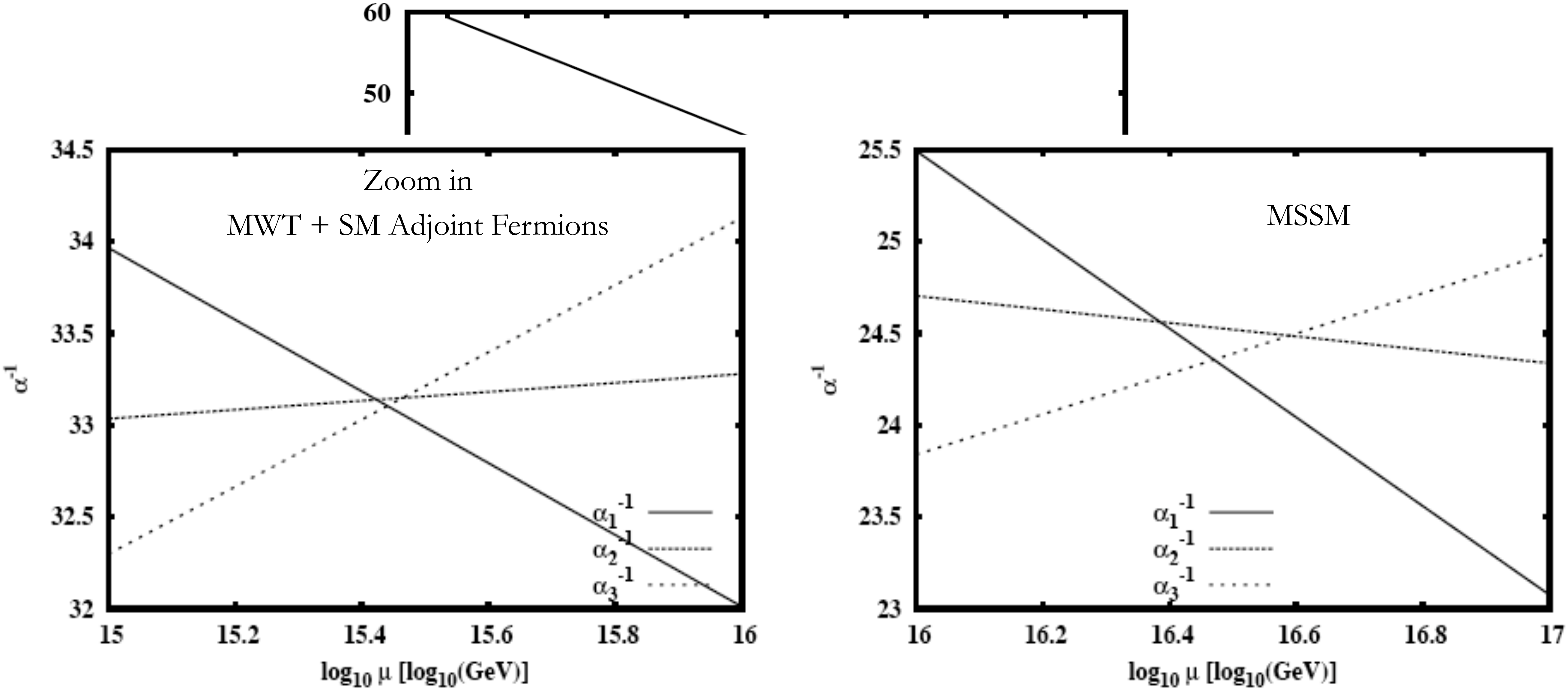
Adding Adjoint SM Matter

Colored Octet of Majorana Particles

Weak Triplet of Majorana Fermions

Extra SM Weyl Singlet

MWT + SM Adjoint Fermions



What LHC can see and how may it deceive you

- Composite States: Technirho, composite (light) Higgs
- Detect Light Higgs: “Elementary or Composite ?”
- Study: pp -> HW,   pp -> HZ.   pp->HW (enhanced)
- 4th Family of Leptons no Quarks

What LHC can see and how may it deceive you

- wino/bino/gluino-like produced. Have you seen SUSY, WTC or ... ?

- Study their couplings to SM fermions

Unpleasant scenario:

- WW scatttering is unitarized at the tree level up to 4 TeV with new vectors states of about 1.5 TeV. LHC and ILC will not dicover! (Foadi and FS 08)

Summary

- Discussed some SM basics and introduced the Origin of Mass Problem
- Minimal Walking Technicolor, A new LHC benchmark
- Dark Matter as a technibaryon
- Unification