Beyond the Standard Model

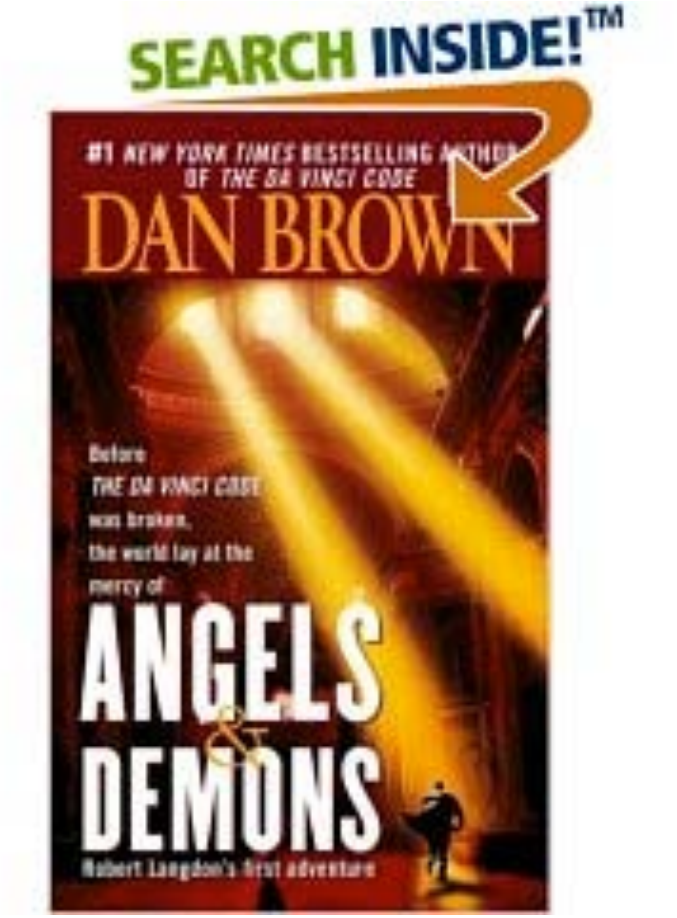
Strong Interactions: From QCD to LHC

Francesco Sannino

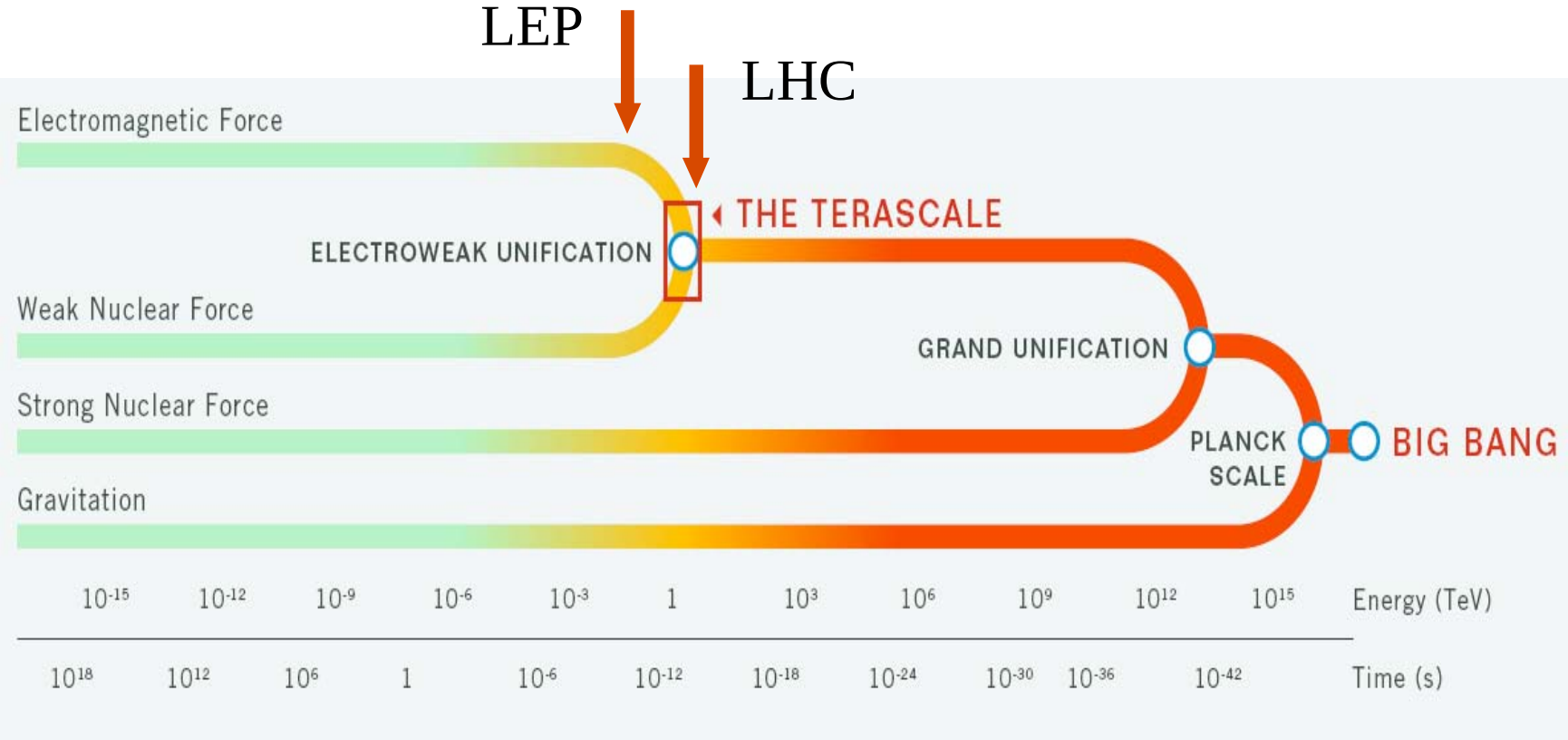
Napoli, Gennaio 2007

In Fiction Books

Angels & Demons



Forces of Nature

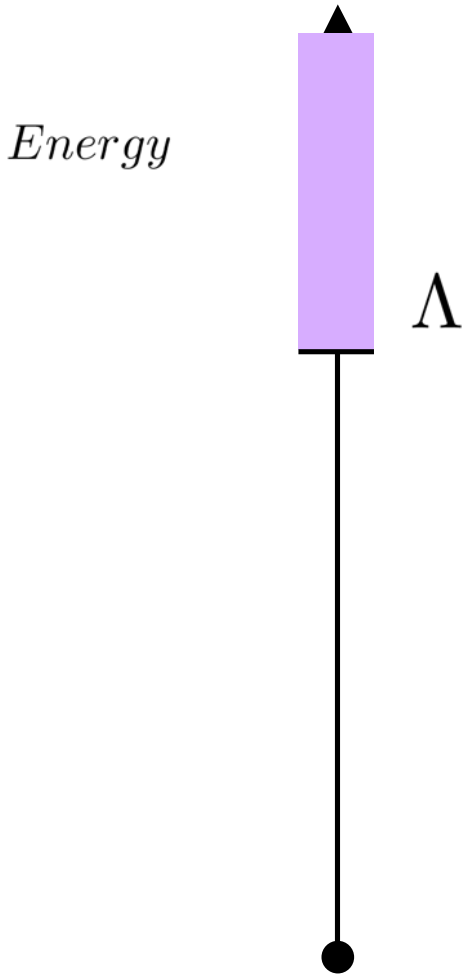


Present situation

- Standard model of Particle Interactions
- Standard Model for an ‘Inflationary’ Universe.
- Both are incomplete.

Facts

Low Energy Effective Theory



….is not so standard

- Origin of Mass of weak gauge bosons, quarks and leptons is unknown.
- Strong Interactions are not fully understood/explored.
- Unnaturally small Neutron Electric Dipole Moment
  Strong CP problem:

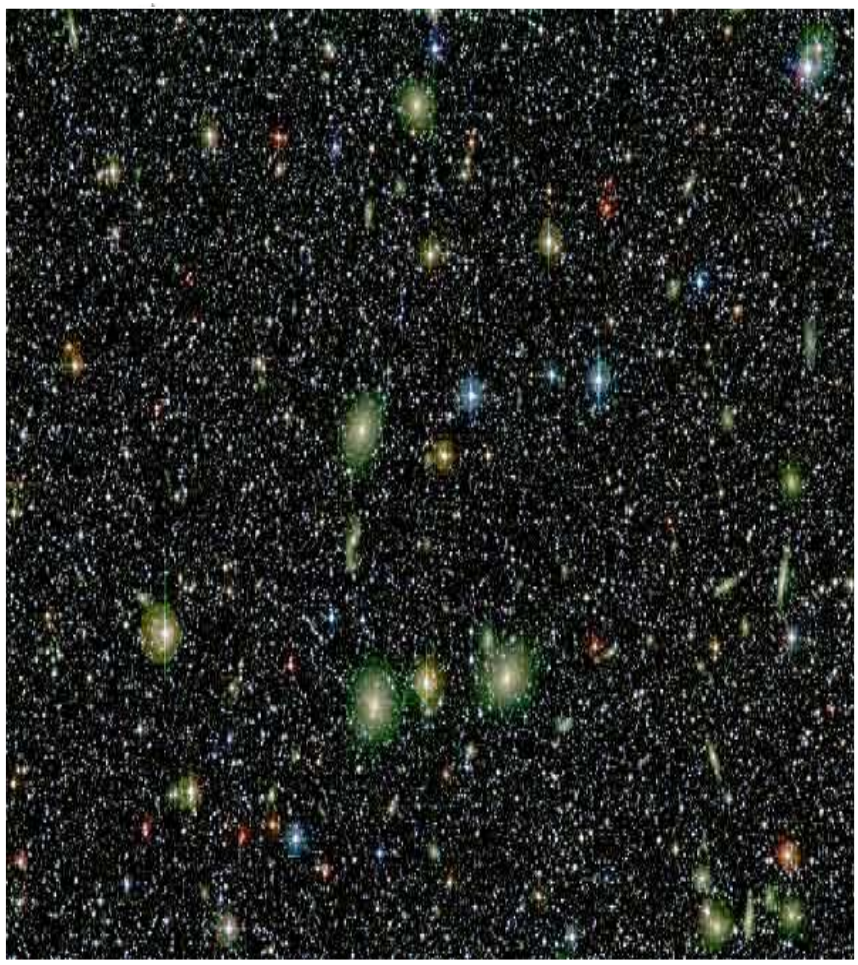
New Challenges from Cosmology.

- Dark Energy/Matter

Mass: A common Problem!

- Mechanism for providing a mass for all of the known particles.

- Still this would not account for the whole matter (Dark Matter) in the Universe.



Cosmological Constant Problem

- Why is empty space so nearly empty?

$$\rho_{vac} < 10^{-46} \text{GeV}^4 \approx 10^{-29} \text{ g cm}^{-3}$$

- Standard Model sets the scale to:

$$\rho_{sm} > 10^{8} \text{GeV}^4$$

- Mismatch by 54 order of magnitude!!

$$\Lambda = \frac{8\pi G_{\text{Newton}}}{c^4} \varrho_{\text{vac}}$$

Let there be Mass

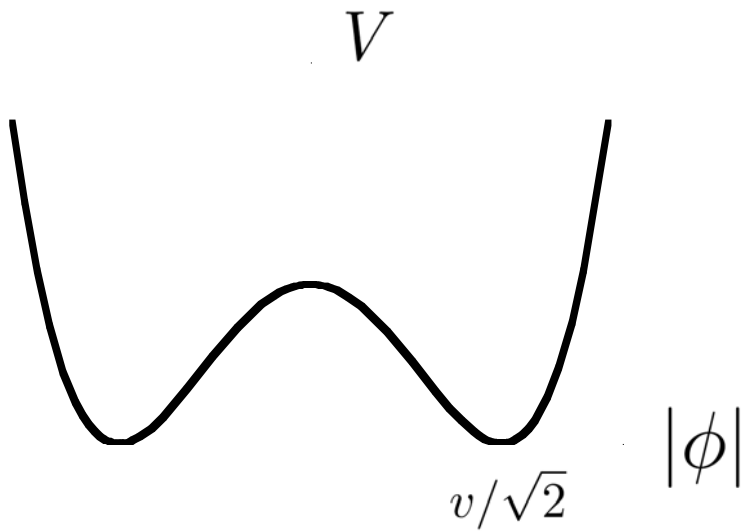
The Mechanism in SM

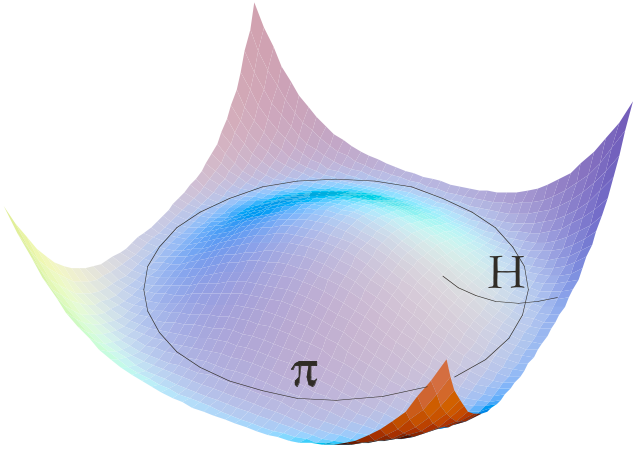
$$V = \frac{\lambda}{2}\left[|\phi|^2 - \frac{v^2}{2}\right]^2$$

$$\phi \to [0\,,\, v + H]\,/\sqrt{2}$$

$$v = 1/\sqrt{\sqrt{2}G_F} \approx 246\ \text{GeV}$$

$$M_H^2 = \lambda\, v^2$$





Gauge Boson-Masses

$$D_\mu \phi = \left(\partial_\mu - igW_\mu^a \tau^a - i\frac{1}{2} g' B_\mu \right) \phi$$

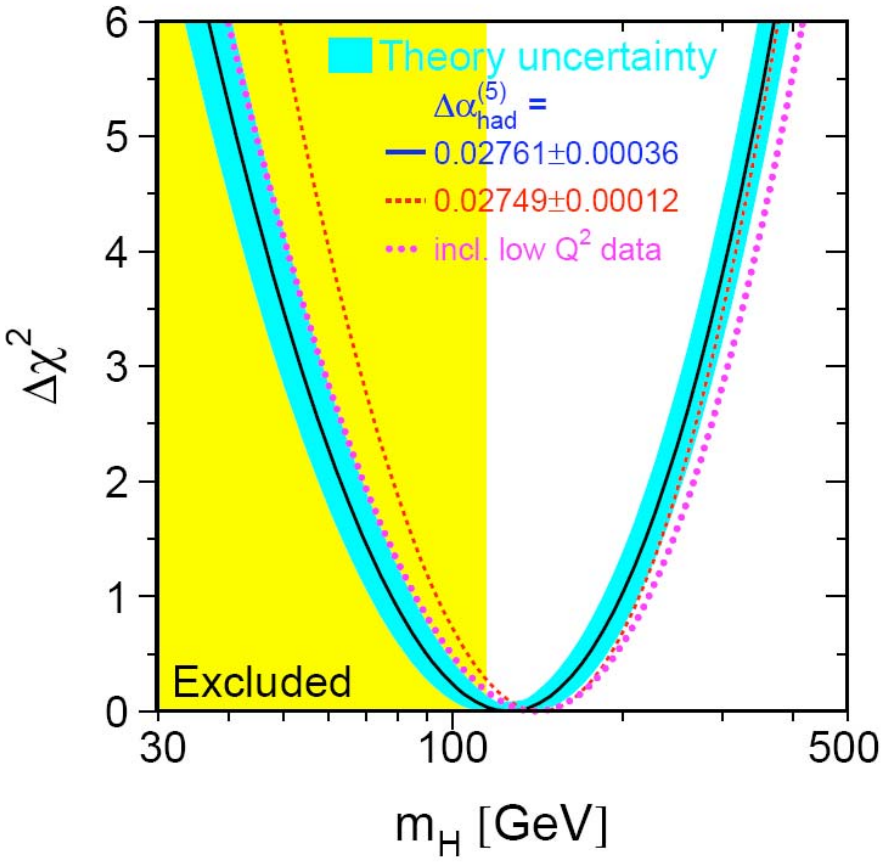
$$D^\mu \phi^\dagger D_\mu \phi \longrightarrow M_W = gv/2 = M_z \cos\theta_w$$

$$e = g\, sin\theta_w \qquad \cos\theta_w = g/\sqrt{g^2 + g'^2}$$

Quark-Masses

$$-\lambda_d \bar{Q}_L \cdot \phi d_R \longrightarrow m_d = \lambda_d\, v/\sqrt{2}$$

SM Higgs: Current Status:

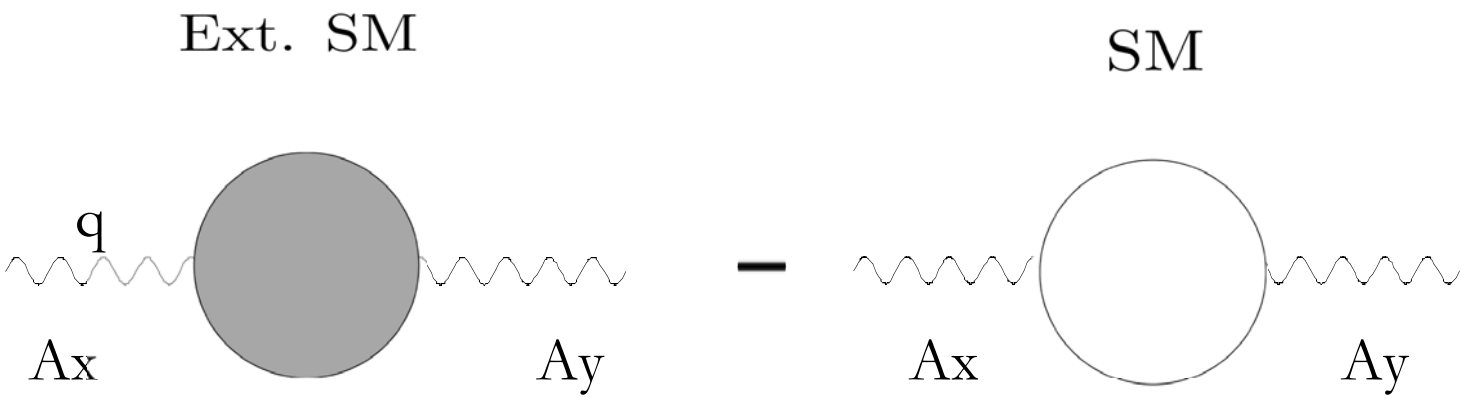


hep-ex/0509008

Can we already test new extensions of the Standard Model?

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

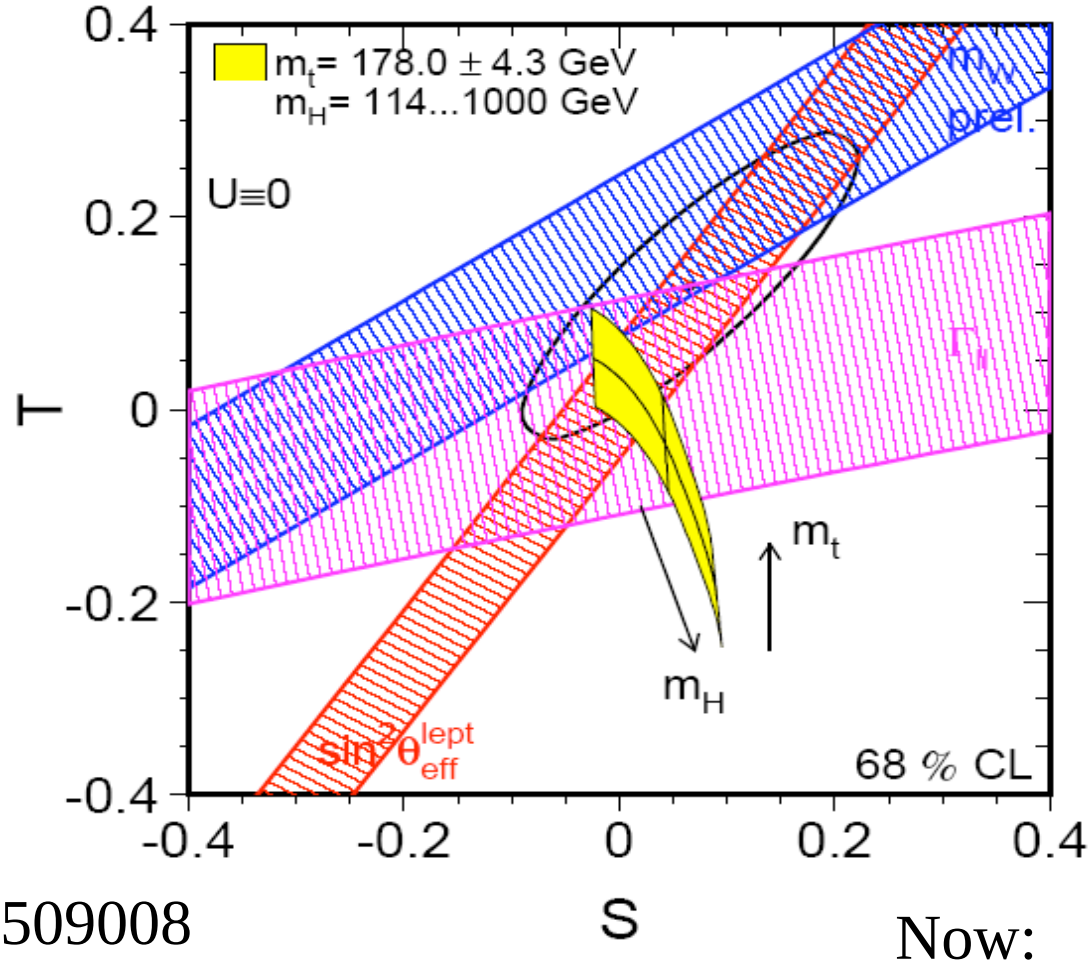
S-measures the left - right type current correlator

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

T-measures deviations from $M_W^2 = \sin^2\theta_w M_Z^2$

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

Present Data



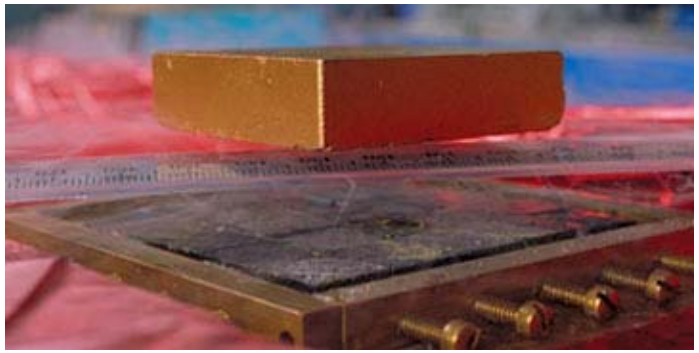
m_H=150 GeV

hep-ex/0509008

Now: S = 0.07±0.10

Dutta, Hagiwara and Yan ph/0603038.Weaken constraints

The Higgs Mechanism in Nature



Superconductivity

Macroscopic-Screening
Non-Relativistic

SM-Screening
Relativistic

$$T < T_c$$

$n_s =$ Density SC electrons

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

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

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

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

$$M_W \sim 80\ GeV$$

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

????

The Higgs-Kibble Mechanism

How does it work?

Imagine you are at Hollywood waiting for your favorite Star (say Brad Pitt = quark, weak gauge boson) to appear.

When Brad appears people start gathering around.

People clusters around Brad and he will move slowly.

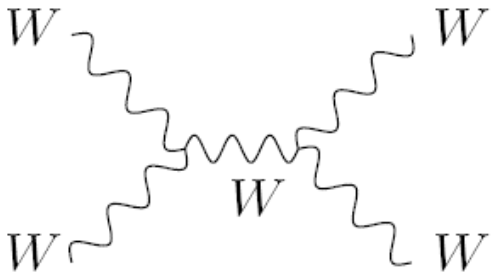
Imagine a world without the Higgs Mechanism

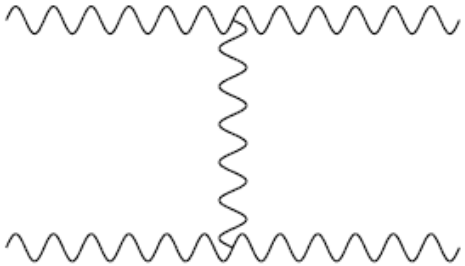
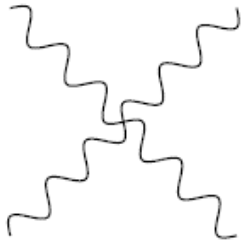
Profound Changes in Nature

- Proton outweighs neutrons
- No hydrogen atom
- Infinite Bohr Radius
- No chemistry, no stable composite structures like solids, liquids..

Scale of New Physics!

WW scattering



S-wave amplitude:

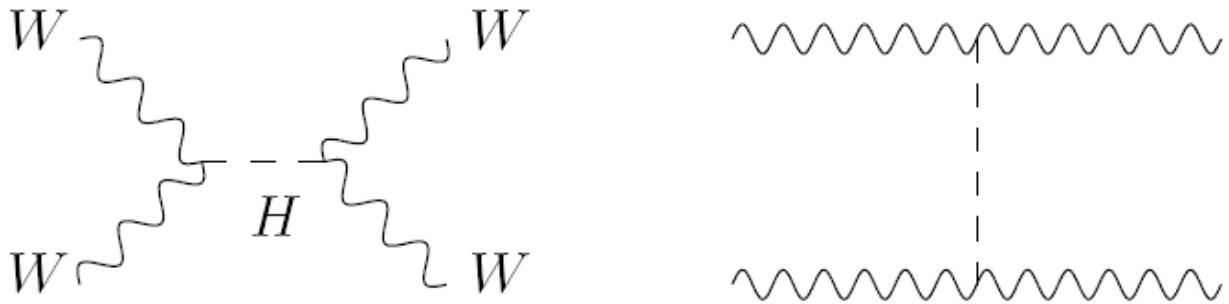
$$A_0 = \frac{G_F}{8\pi\sqrt{2}}\, s \qquad G_F = \frac{g^2}{4\sqrt{2}M_W^2}$$

$$\simeq 1.14 \times 10^{-5}\mathrm{GeV}^{-2}$$

Unitarity:

$$\Re\left[A_0\right] \leq \frac{1}{2} \quad \longrightarrow \quad s \leq 4\pi\sqrt{2}/G_F \sim (1.2\ \mathrm{TeV})^2$$

.....



$$A_0' = -\frac{G_F}{8\pi\sqrt{2}}\, s$$

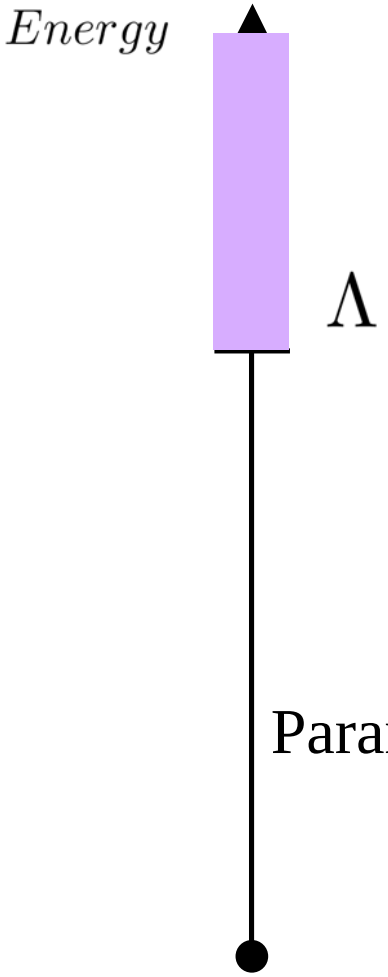
Theorem:

Unitarity requires the existence of a weakly coupled Higgs particle or New Physics around the Terascale!

Elementary Higgs:

Trivial and Non-natural

Trivial theory

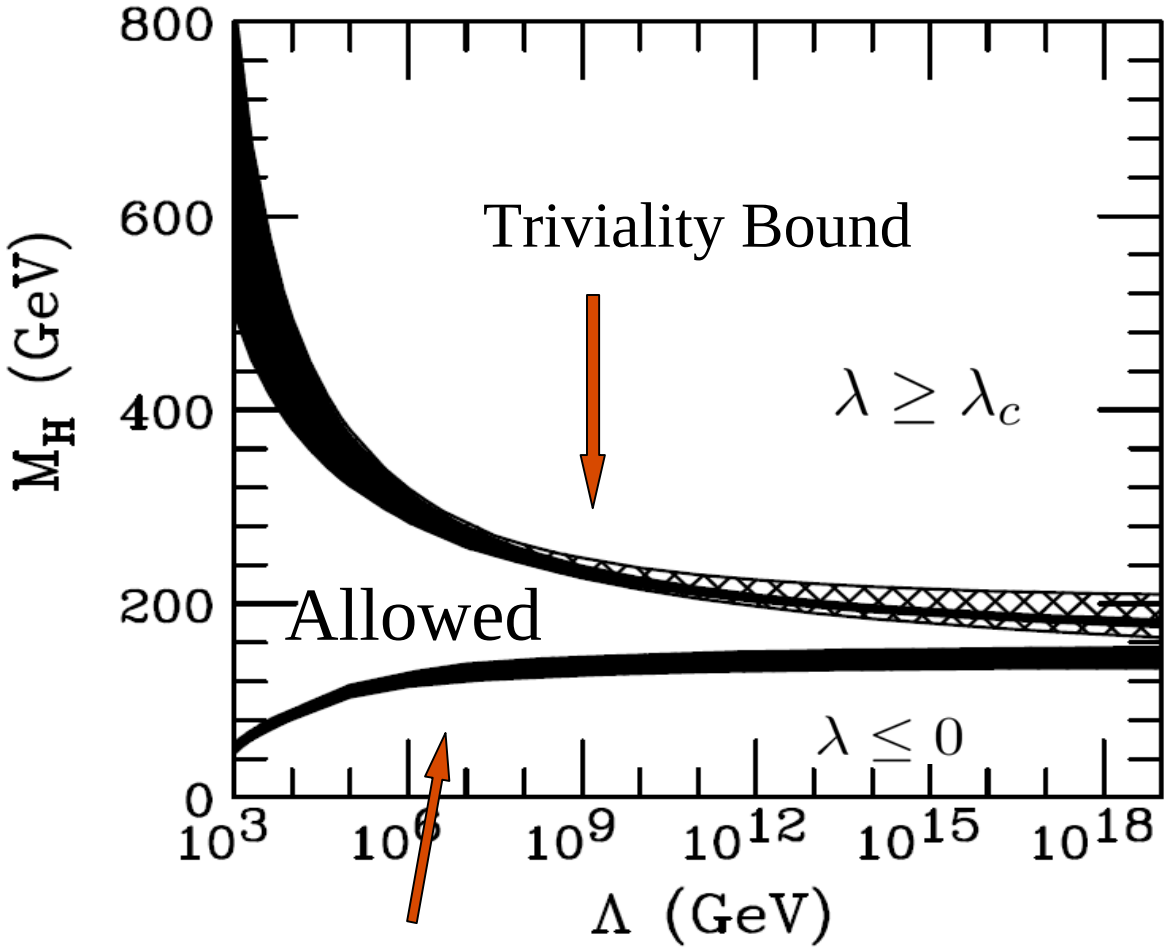


$$\Lambda \to \infty \qquad \lambda \to 0$$

No Interactions!

$$V = \frac{\lambda}{2}\left[|\phi|^2 - \frac{v^2}{2}\right]^2$$

Perturbative Higgs Window



Stability Bound

Naturality

Small parameters stay small under radiative corrections.

Is the Higgs Natural?

No *custodial* symmetry *protecting* a scalar mass.

$$M_{H\,R}^2 = R \times M_{H\,B}^2 + \Lambda^2$$

A mass appears even if *ab initio* is set to zero!

Hierarchy between the EW scale and the Planck Scale.

No!

Natural Scalars

Exact Super Symmetry:

Fermions ↔ Bosons

Fermion's *custodial symmetry* protects the Bosons

Observe: susy partners

Composite Scalar:

Recall Superconductivity

Substructure resolved at scale Λ_S

$$M_{H\,R}^2 = R \times M_{H\,B}^2 + \Lambda_S^2$$

Observe: New Bound States

Quasi Goldstone Boson:

Protected by spontaneously broken global symmetries.

Near Continuous Quantum Phase Transition

$$M_H^2 = \Lambda^2 (t_c - t)^\nu$$

Zero-temperature Bose – Einstein Condensation
Lorentz symmetry is broken.

Chiral Phase Transition at zero temperature.
Lorentz symmetry is intact.

Electroweak Symmetry Breaking

@

LHC

Electroweak Symmetry Breaking

SUSY

Technicolor

Extra Dim.

Curved

Flat

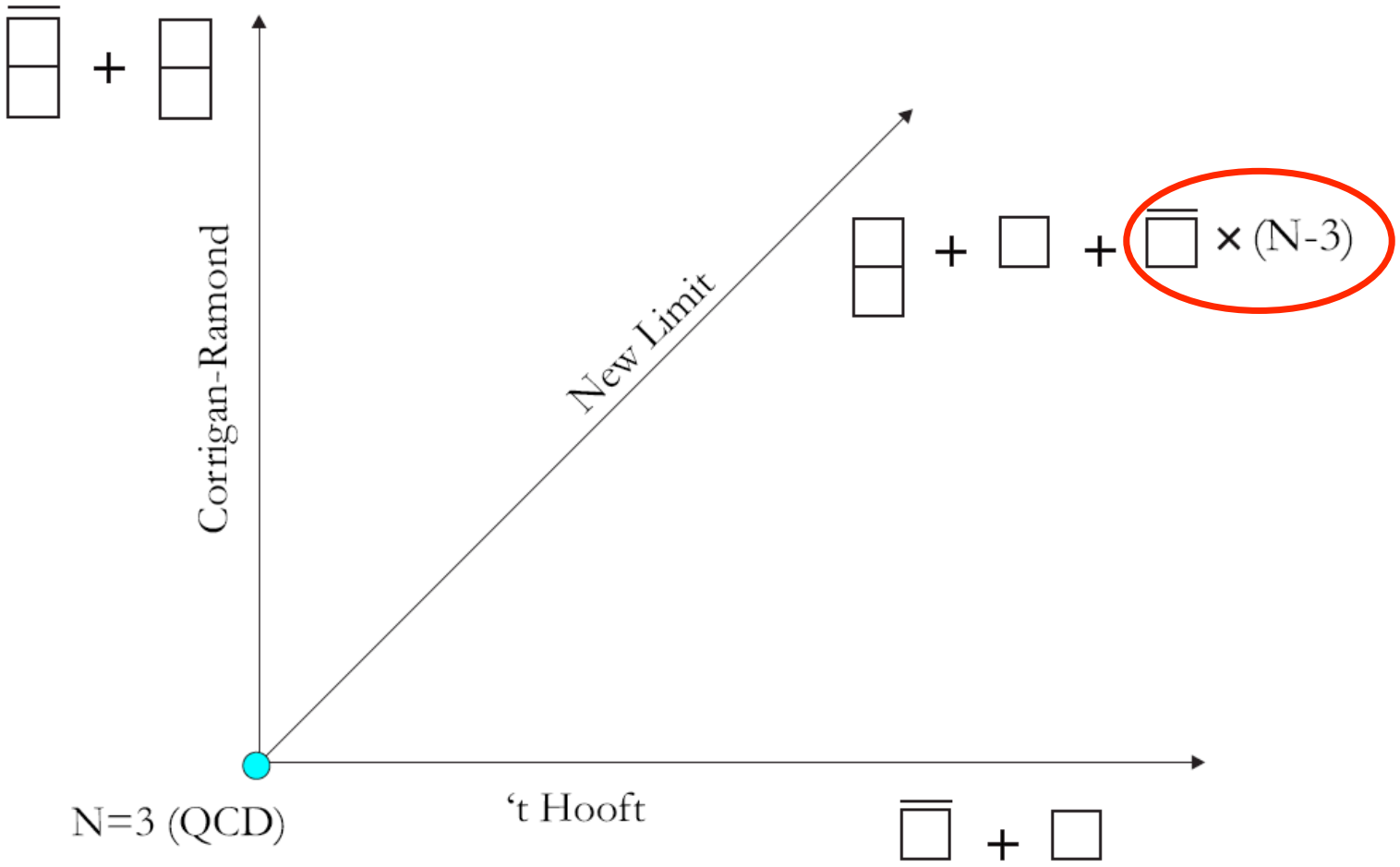
Progress in Strong Interactions

New Limits for Strongly Interacting Theories

We have provided a link between Confinement and Chiral Symmetry.

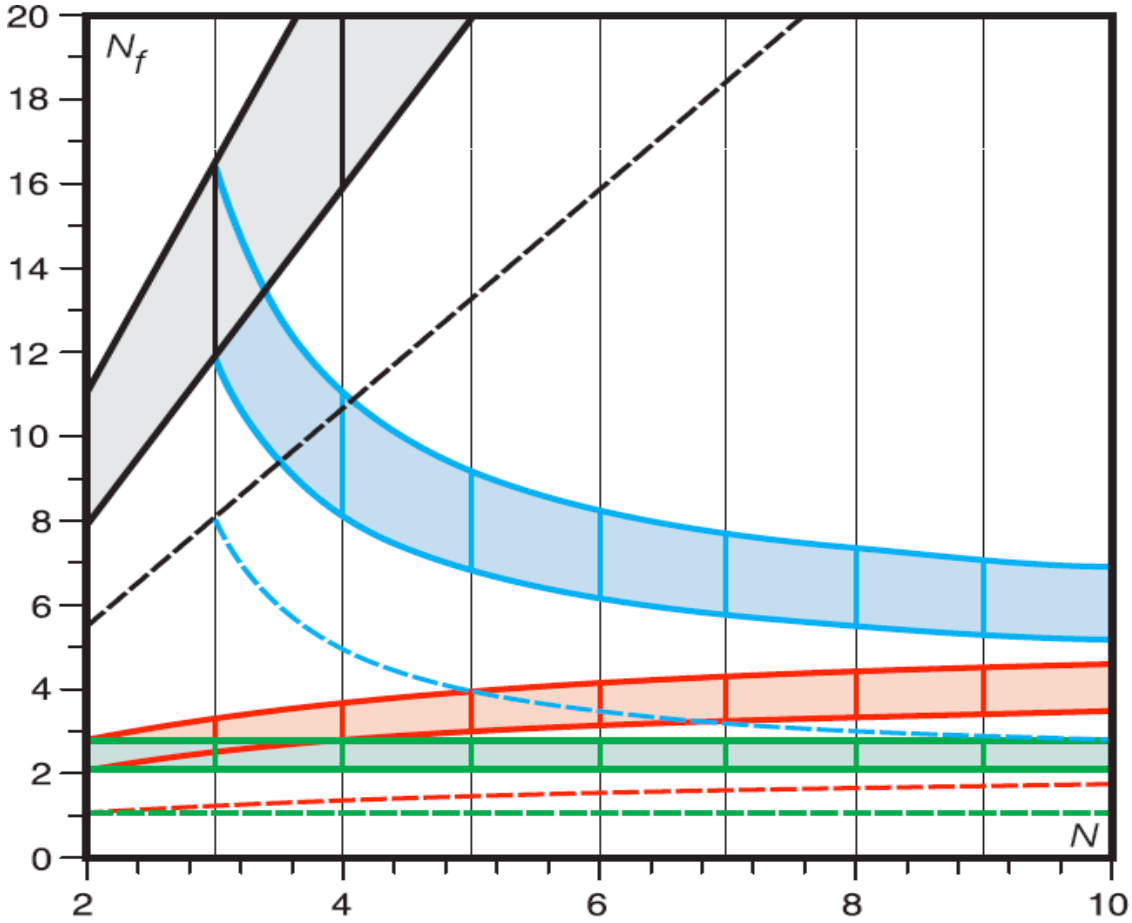
We have unveiled the Phase Diagram of Higher Dimensional Representations

Novel Limit



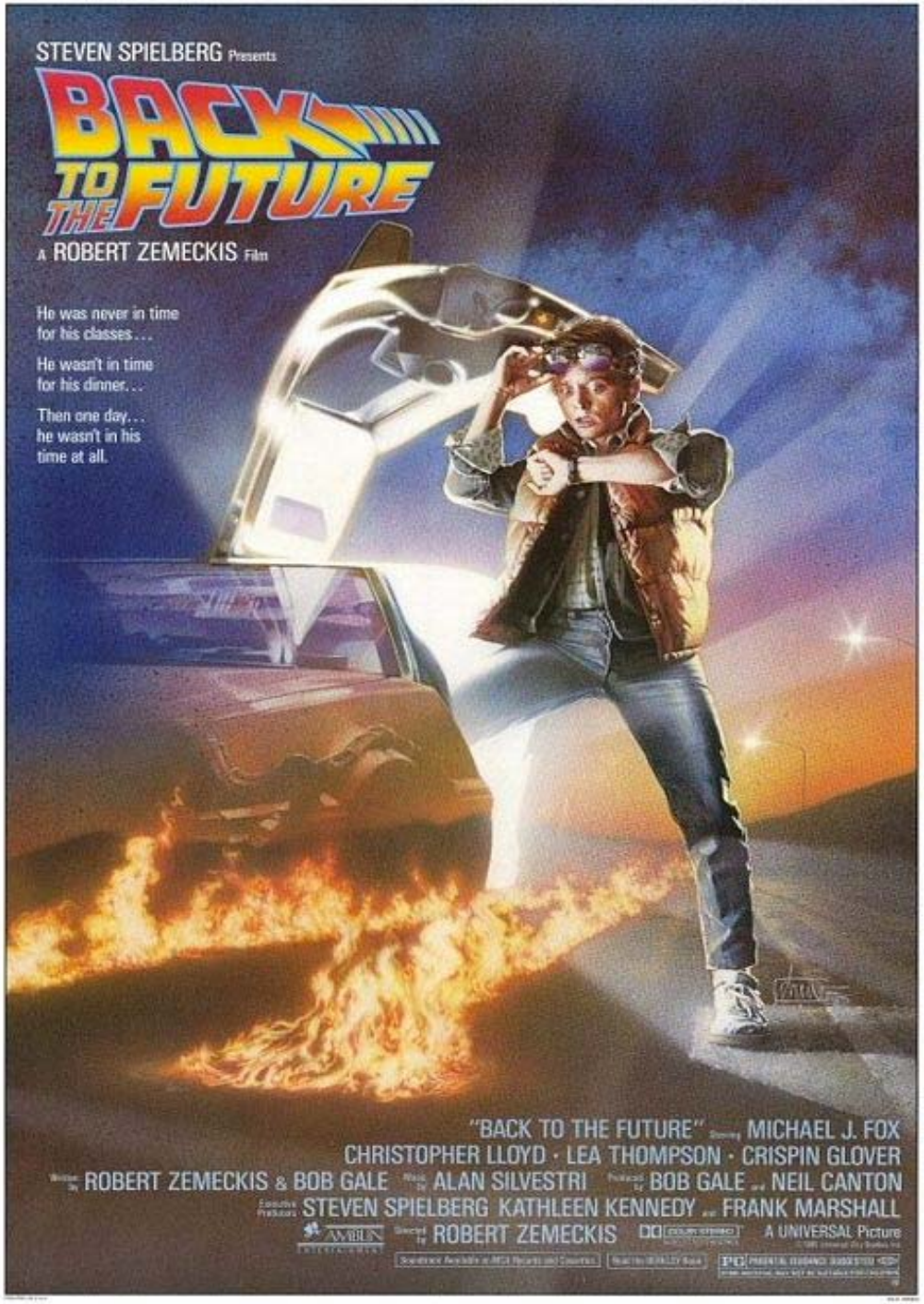
Ryttov and F.S. th/0509130

Universal Phase Diagram for HDRs



Dietrich-F.S. hep-ph/0611341

Phase diagram for theories with fermions in the
Fundamental (Black-gray), 2A (Blue-light blue), 2S (Red-pink),
Adjoint (Green - light green).
For N=4, 6 and 8 also the 3-index antisymmetric has a nontrivial phase diagram.


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 and NEIL CANTON
STEVEN SPIELBERG KATHLEEN KENNEDY and FRANK MARSHALL
ROBERT ZEMECKIS
A UNIVERSAL Picture

Technicolor

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

Natural to use QCD-like dynamics.

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

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

Nf=2 & N=2:

Minimal-Walking/Working-Theory

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

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

Universal critical number of flavors in the adjoint: Nfc=2.075

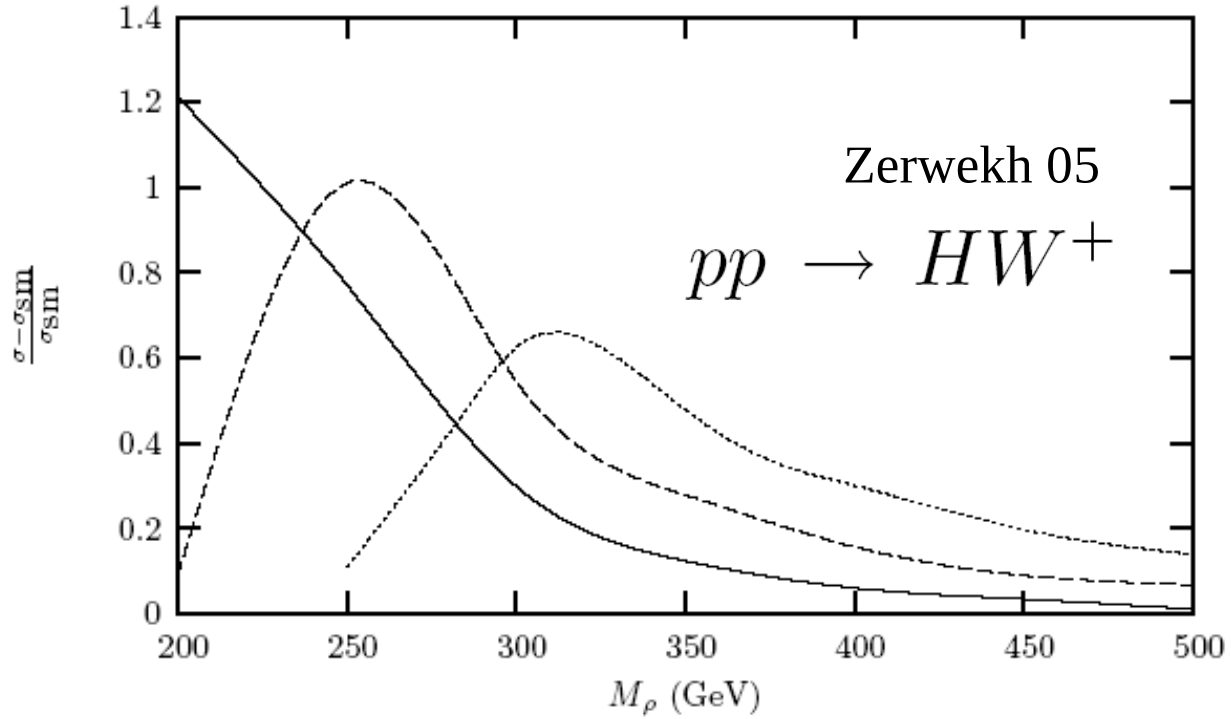
Within 68% Confidence Level of EWPD

Sannino-Tuominen

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

A natural LCH*
&
Large Production at Tevatron and CERN

	QCD-like	WTC(3, 11)	WTC(2, 7)	S(3, 2)	S(2, 2)
$m_H(\text{GeV}) \approx$	1000	400	300	170 – 300	90 – 150



$M_H = 115$ GeV (solid line), 150 GeV (dashed line) and 200 GeV (dotted line)

Dark Side of the 5th Force

Nussinov
Barr, Chivukula and Farhi
Gudnason, Kouvaris and F.S.

$$\frac{\Omega_{TB}}{\Omega_B} = \frac{TB}{B}\frac{m_{TB}}{m_p} \ , \qquad m_{TB} \text{ is the mass of the LTB}$$

Technibaryon, DD
(specific choice of the hypercharge)

Universe Charge Neutrality.
Chemical Equilibrium
Taking care of the Sphaleron Processes

1st Order

$$-\frac{TB}{B} = \sigma_{DD}\frac{22+\sigma_{\nu'}}{9(22+2\sigma_{DD}+\sigma_{\nu'})}\left[3+\frac{L}{B}+\frac{1}{\sigma_{\nu'}}\frac{L'}{B}\right]$$

$$\sigma_i = \begin{cases} 6\mathscr{F}\left(\frac{m_i}{T^*}\right) & \text{for fermions ,} \\ 6\mathscr{G}\left(\frac{m_i}{T^*}\right) & \text{for bosons ,} \end{cases}$$

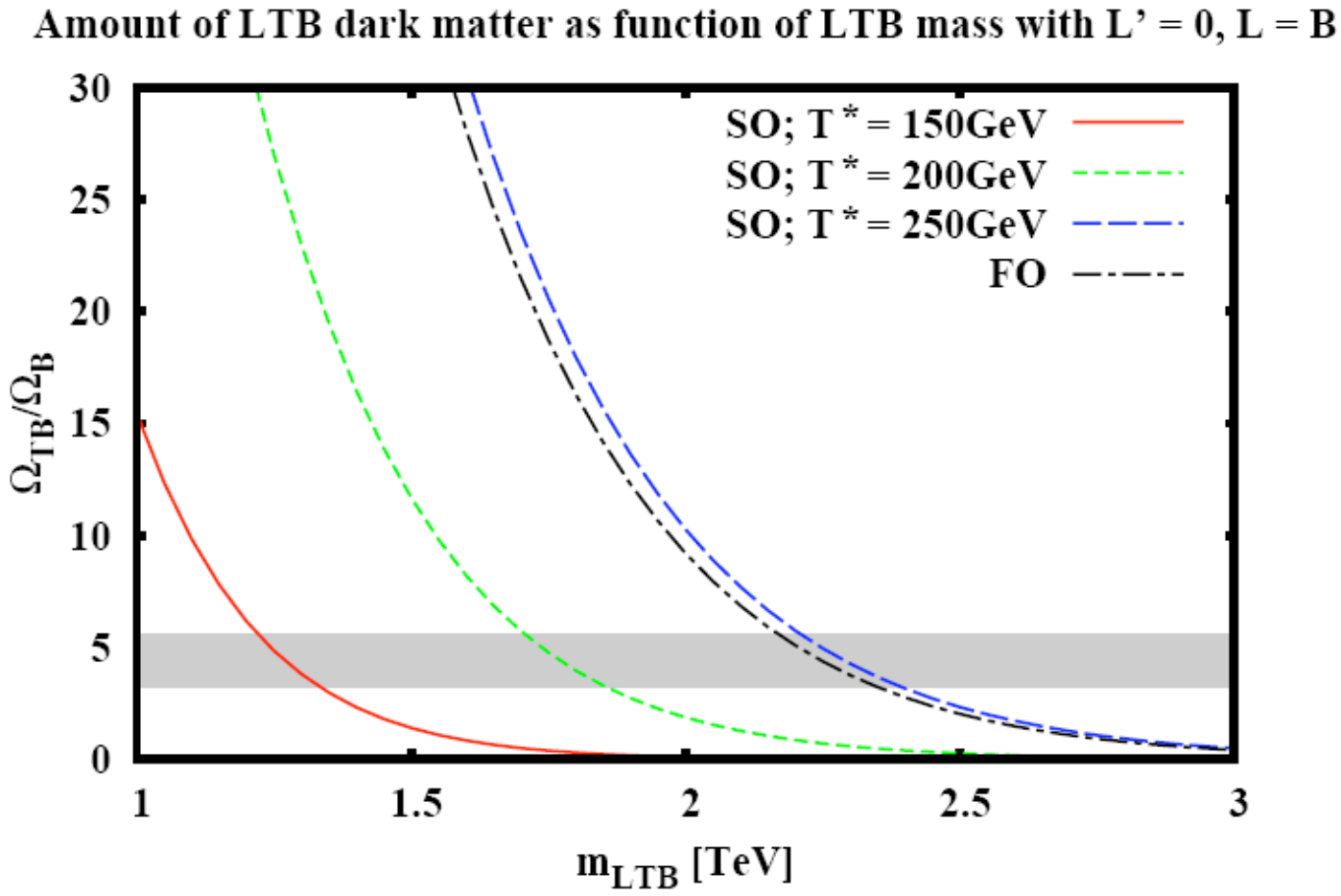
$$\mathscr{F}(z) = \frac{1}{4\pi^2}\int_0^\infty dx\, x^2 \cosh^{-2}\left(\frac{1}{2}\sqrt{x^2+z^2}\right)$$

$$\mathscr{G}(z) = \frac{1}{4\pi^2}\int_0^\infty dx\, x^2 \sinh^{-2}\left(\frac{1}{2}\sqrt{x^2+z^2}\right)$$

2nd Order

$$-\frac{TB}{B} = \frac{\sigma_{DD}}{3(18+\sigma_{\nu'})}\left[(17+\sigma_{\nu'}) + \frac{(21+\sigma_{\nu'})}{3}\frac{L}{B} + \frac{2}{3}\frac{(9+5\sigma_{\nu'})}{\sigma_{\nu'}}\frac{L'}{B}\right]$$

Dark Side of the 5th Force



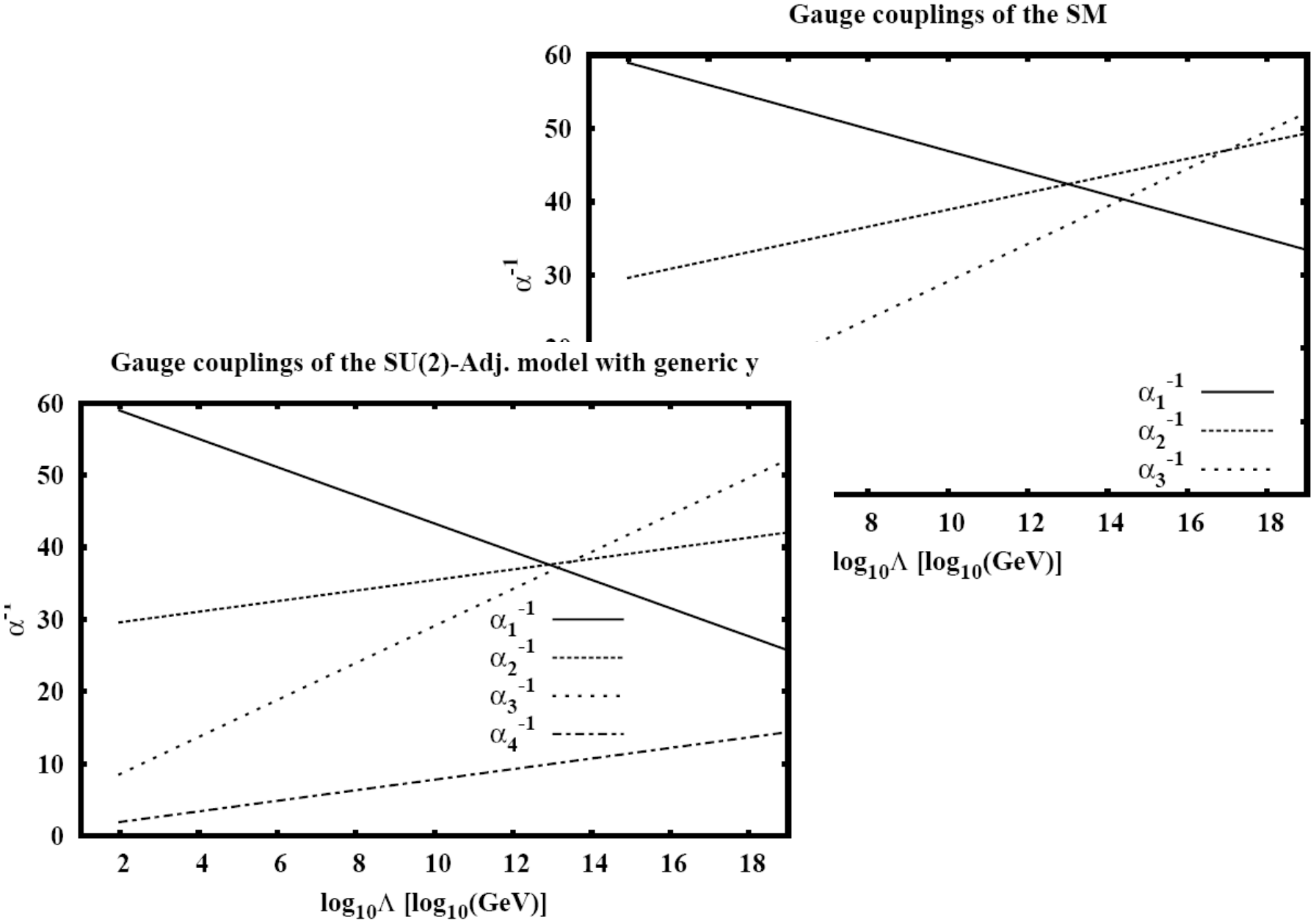
Technibaryon, DD

Gudnason, Kouvaris and F.S. ph/0608055

Unification

Technicolor assisted Unification

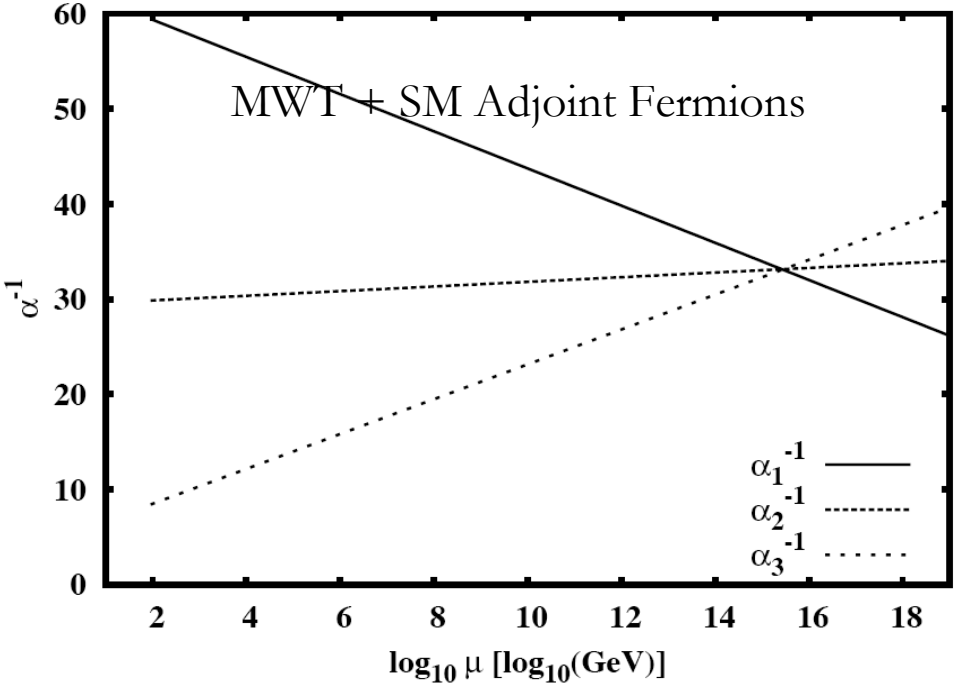
Gudnason, Ryttov, F.S.

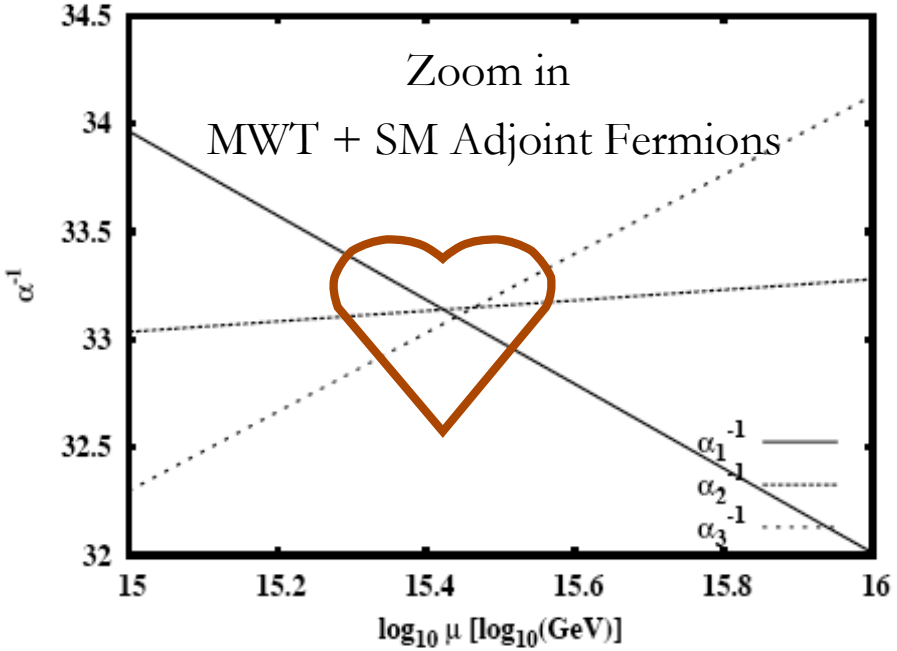

Gauge couplings of the SM
60
50
40
30
α^{-1}
α_1^{-1}
α_2^{-1}
α_3^{-1}
8
10
12
14
16
18
$\log_{10}\Lambda$ [$\log_{10}$(GeV)]
Gauge couplings of the SU(2)-Adj. model with generic y
60
50
40
30
20
10
0
α^{-1}
α_1^{-1}
α_2^{-1}
α_3^{-1}
α_4^{-1}
2
4
6
8
10
12
14
16
18
$\log_{10}\Lambda$ [$\log_{10}$(GeV)]

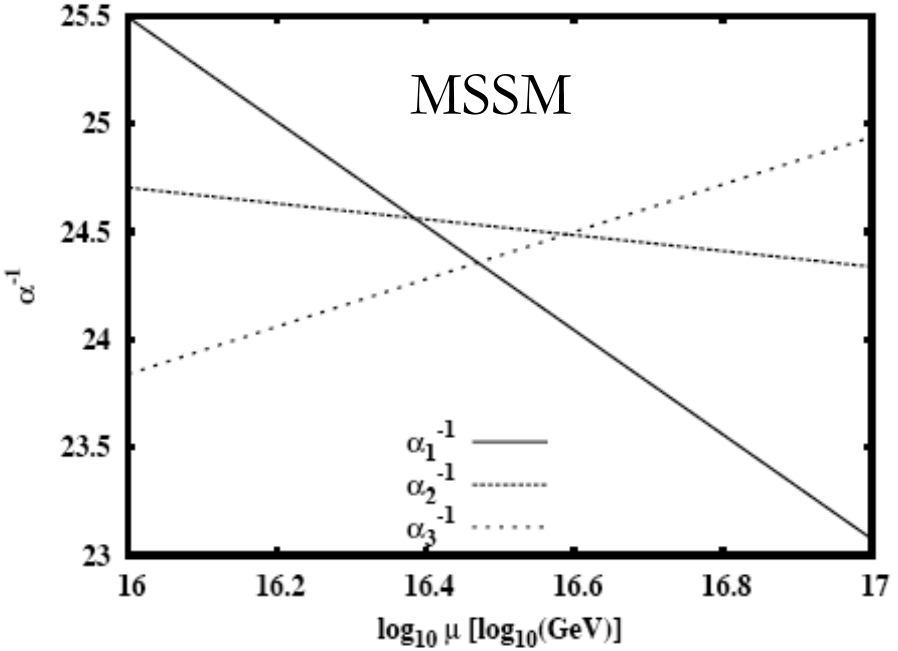
Perfecting Unification

Just add a gluino and a wino!

Gudnason, Ryttov, F.S. ph/0612230


MWT + SM Adjoint Fermions
60
50
40
30
20
10
0
2
4
6
8
10
12
14
16
18
α^{-1}
$\log_{10} \mu$ [$\log_{10}$(GeV)]
α_1^{-1}
α_2^{-1}
α_3^{-1}


Zoom in
MWT + SM Adjoint Fermions
34.5
34
33.5
33
32.5
32
15
15.2
15.4
15.6
15.8
16
α^{-1}
$\log_{10} \mu$ [$\log_{10}$(GeV)]
α_1^{-1}
α_2^{-1}
α_3^{-1}


MSSM
25.5
25
24.5
24
23.5
23
16
16.2
16.4
16.6
16.8
17
α^{-1}
$\log_{10} \mu$ [$\log_{10}$(GeV)]
α_1^{-1}
α_2^{-1}
α_3^{-1}


LHC
SUSY
TC
ED

Predictions and Outlook

- $M_H \sim$ light
- Fourth Family of Leptons around the Z mass
- 6 light scalars will be observed.
- Electroweak baryongenesis.
  Possible Strongly First order phase transition.
- Lattice Simulations are running!
- DM candidate-component
- Perfect Unification! MWT + adjoint fermions

Technicolor is the renaissance of Strong Interactions

The School of Athens - fresco by Raffaello Sanzio