Non-Standard Electroweak Symmetry Breaking

Higgs-Maxwell Particle Physics Workshop
Royal Society of Edinburgh
13 February, 2008

Christophe Grojean
CERN-TH & CEA-Saclay-IPhT
(Christophe.Grojean[at]cern.ch)
A Central Question in Particle Physics

Astro/Cosmo data (Dark matter and baryon asymmetry) + theoretical prejudice (hierarchy/naturality)

strongly suggest the presence of New Physics around the weak scale that is supposed to play a crucial role in breaking the electroweak symmetry

What is the mechanism of EW symmetry breaking?

often said that the LHC is built to address this question
What is the mechanism of EWSB?

what we usually mean by that question is

what is cancelling the Higgs $\Lambda^2$ divergences?
what is ensuring the stability of the weak scale?

This cancellation requires new symmetries among the TeV scale population
How to Stabilize the Higgs Potential

Goldstone's Theorem

spontaneously broken global symmetry $\Rightarrow$ massless scalar

... but the Higgs has sizable non-derivative couplings

The Spin Trick

a particle of spin $s$: $\Rightarrow$ fewer polarization states

2s+1 polarization states

... with the only exception of a particle moving at the speed of light

Spin 1 $\Rightarrow$ no longitudinal polarization

Gauge invariance

Spin 1/2 $\Rightarrow$ only one helicity

Chiral symmetry

... but the Higgs is a spin 0 particle

$m=0$
Symmetries to Stabilize a Scalar Potential

Supersymmetry

fermion ~ boson

Higher Dimensional Lorentz invariance

\[ A_\mu \sim A_5 \]

4D spin 1 \quad 4D spin 0

These symmetries cannot be exact symmetry of the Nature. They have to be broken. We want to look for a soft breaking in order to preserve the stabilization of the weak scale.

[References: Manton '79, Fairlie '79, Hosotani '83 +...]

Christophe Grojean

Non-Standard EWSB

Edinburgh, February 13th 2008
It was known since Pauli-Villars that ghosts can soften the UV behavior of the propagators. But they are unstable per se.

Lee-Wick in the 60’s proposed a trick to stabilize the ghosts (at the price of a violation of causality at the microscopic scale).
Little Higgs Models

Higgs as a pseudo-Nambu-Goldstone boson

QCD: $\pi^+, \pi^0$ are Goldstone associated to $SU(2)_L \times SU(2)_R$

$$\alpha_{em} \to 0, \; m_q \to 0 \quad \alpha_{em} \neq 0$$

LxR exact
$$m_\pi = 0$$

$m^2_{\pi^\pm} \approx \frac{\alpha_{em}}{4\pi} \Lambda^2_{QCD}$

EW pions

$$\alpha_{top} \to 0, \; g, \; g' \to 0$$

exact global sym.

$$m^2_H \approx \frac{\alpha_{top}}{4\pi} \Lambda^2_{strong}$$

would require
$$\Lambda_{strong} \sim 1 \; \text{TeV}$$

...too low!

Little Higgs = PNGB + Collective Breaking

$$m^2_H \approx \frac{\alpha_i \alpha_j}{(4\pi)^2} \Lambda^2_{strong}$$

[Arkani-Hamed et al. ‘02]
Little Higgs = PNGB + Collective Breaking

\[ \text{Higgs} \in G/H \]

The coset structure is broken by 2 sets of interactions

\[ \mathcal{L} = \mathcal{L}_{G/H} + g_1 \mathcal{L}_1 + g_2 \mathcal{L}_2 \]

each interaction preserves a subset of the symmetry

Higgs remains an exact PNGB when either \( g_1 \) or \( g_2 \) is vanishing

\[ \text{SU}(5)/\text{SO}(5) \]

24-10=14 PNGB

gauge SU(2)_L \times SU(2)_R subgroup (broken to SU(2)_D)

14-3=11 PNGB left = 3_1, 2_{1/2}, 1_0

if \( g_L \) or \( g_R \) vanishes, SU(3)/SU(2) coset intact and Higgs remains massless
Twin Higgs = PNGB + Discrete Symmetry

[Chacko, Goh, Harnik ‘05]

Higgs ∈ $G/H$

new interactions break the coset and generate a potential for the Higgs
discrete symmetry among these interactions
⇒ enlarged symmetry of the Higgs potential

SU(4)/SU(3)

gauche $SU(2)_L \times SU(2)_R$ subgroup with $L \leftrightarrow R$
the potential is automatically $SU(4)$ invariant

cancelation of $\Lambda^2$ divergences by new particles which are SM singlets

avoid conflict with EW precision tests
Cancellation of $\Lambda^2$ divergences

- Supersymmetry: cancellation by opposite spin particles
  - top loop cancelled by stop loop
  - Higgs loop cancelled by higgsino loop
  - gauge boson loops cancelled by gaugino loops

- Little Higgs: cancellation by same spin particles
  - top loop cancelled by heavy top loop
  - Higgs loop cancelled by heavy singlet/triplet scalars
  - gauge boson loops cancelled by heavy gauge boson loops

- Gauge-Higgs unification: cancellation by same spin particles
  - top loop cancelled by heavy top loop
  - Higgs loop cancelled by heavy gauge boson loop
  - gauge boson loops cancelled by heavy gauge boson loops
What is unitarizing the WW scattering amplitudes?

Weakly coupled models

\[ \epsilon_l = \left( \frac{|\vec{k}|}{M}, \frac{E}{M} \frac{k}{|\vec{k}|} \right) \]

Strongly coupled models

\[ A = g^2 \left( \frac{E}{M_W} \right)^2 \]

other ways?

**Weakly coupled models**

prototype: Susy

susy partners \( \sim 100 \) GeV

**Strongly coupled models**

prototype: Technicolor

rho meson \( \sim 1 \) TeV

Higgs sector interactions

(we have already discovered 75% of the Higgs doublet!)

WW scattering is a probe of Higgs sector interactions

What is the mechanism of EWSB?

All these models assume that we already know the answer to
Strongly coupled models

a phenomenological challenge: how to evade EW precision data

The resonance that unitarizes the WW scattering amplitudes generates a tree-level effect on the SM gauge bosons self-energy

\[ \text{TC} = \frac{w_-}{w^+} + \ldots \]

S parameter of order 1.
Not seen at LEP

a theoretical challenge: need to develop tools to do computation
Back to “Technicolor” from Xdims

“AdS/CFT” correspondence for model-builder

Warped gravity with fermions and gauge field in the bulk and Higgs on the brane

\[ A_5 \rightarrow A_5 + \partial_5 \epsilon \]

Strongly coupled theory with slowly-running couplings in 4D

\[ h \rightarrow h + a \]

to pseudo-Goldstone of a strong force

Advantages

- hierarchy problem addressed + gauge coupling unification
- weakly coupled description ☻ calculable models
- new approach to fermion embedding and flavor problem

Christophe Grojean

Non-Standard EWSB

Edinburgh, February 13th 2008
Higgsless Models

The LHC might not see anything beyond the Standard Model...
Warped Higgsless Model

**UV brane**
\[ z = R_{UV} \sim 1/M_{Pl} \]

**SU(2)_L \times SU(2)_R \times U(1)_{B-L}**

\[ A^R_{\mu} = 0 \]
\[ g'_5 B_\mu - g_5 A^R_{\mu} = 0 \]
\[ \partial_5 (g_5 B_\mu + g'_5 A^R_{\mu}) = 0 \]

**IR brane**
\[ z = R_{IR} \sim 1/TeV \]

**U(1)_{B-L} \times SU(2)_D**

\[ A^L_{\mu} - A^R_{\mu} = 0 \]
\[ \partial_5 (A^L_{\mu} + A^R_{\mu}) = 0 \]

**U(1)_{em}**

**BCs kill all A_5 massless modes: no 4D scalar mode in the spectrum**

"light" mode:

\[ M^2_W = \frac{1}{R^2_{IR} \log(R_{IR}/R_{UV})} \]

\[ M^2_Z \sim g^2_5 + 2g'^2_5 \frac{R^2_{IR} \log(R_{IR}/R_{UV})}{R^2_{IR}} \]

log suppression

KK tower:

\[ M^2_{KK} = \text{cst of order unity} \]

Christophe Grojean

Non-Standard EWSB

Edinburgh, February 13th 2008
Unitarization of (Elastic) Scattering Amplitude

Same KK mode 'in' and 'out'

\[ \epsilon^\mu = \left( \frac{\vec{p}}{M}, \frac{E}{M} \frac{-\vec{p}}{M} \right) \]

\[ \mathcal{A} = \mathcal{A}^{(4)} \left( \frac{E}{M} \right)^4 + \mathcal{A}^{(2)} \left( \frac{E}{M} \right)^2 + \ldots \]

\[ A^{(4)} = i \left( g^2_{nnnn} - \sum_k g^2_{nnk} \right) \left( f^{abe} f^{cde} (3 + 6c_\theta - c_\theta^2) + 2(3 - c_\theta^2) f^{ace} f^{bde} \right) \]

\[ A^{(2)} = i \left( 4g^2_{nnnn} - 3 \sum_k g^2_{nnk} \frac{M_k^2}{M_n^2} \right) \left( f^{ace} f^{bde} - s_{\theta/2}^2 f^{abe} f^{cde} \right) \]
**KK Sum Rules**

\[
\mathcal{A}^{(4)} \propto g_{nnnn}^2 - \sum_k g_{nnk}^2
\]

\[
\mathcal{A}^{(2)} \propto 4g_{nnnn}^2 - 3 \sum_k g_{nnk}^2 \frac{M_k^2}{M_n^2}
\]

In a KK theory, the effective couplings are given by overlap integrals of the wavefunctions.

\[
g_{mnpq} = g_{5D}^2 \int_{R_{UV}}^{R_{IR}} dz \frac{R}{z} f_m(z) f_n(z) f_p(z) f_q(z)
\]

\[
g_{mnp} = g_{5D} \int_{R_{UV}}^{R_{IR}} dz \frac{R}{z} f_m(z) f_n(z) f_p(z)
\]

**E^4 Sum Rule**

\[
g_{nnnn}^2 - \sum_k g_{nnk}^2 = g_{5D}^2 \int_{R_{UV}}^{R_{IR}} dz \frac{R}{z} f_n^4(z) - g_{5D}^2 \int_{R_{UV}}^{R_{IR}} dz \frac{R}{z} \int_{R_{UV}}^{R_{IR}} dz' f_n^2(z) f_n^2(z') \sum_k \frac{R}{z'} f_k(z) f_k(z') = 0
\]

\[
\sum_k \frac{R}{z'} f_k(z) f_k(z') = \delta(z - z')
\]

Completeness of KK modes

---

Christophe Grojean
Non-Standard EWSB

Csaki, Grojean, Murayama, Pilo, Terning '03
Collider Signatures

unitarity restored by vector resonances whose masses and couplings are constrained by the unitarity sum rules

WZ elastic cross section

\[ g_{WW'Z} \leq \frac{g_{WW'Z} M_Z^2}{\sqrt{3} M_{WW}, M_W} \]

\[ \Gamma(W' \rightarrow WZ) \sim \frac{\alpha M_{W'}^3}{144 s_w^2 M_W^2} \]

a narrow and light resonance

W' production

discovery reach

@ LHC

(10 events)

550 GeV \rightarrow 10 \text{ fb}^{-1}

1 TeV \rightarrow 60 \text{ fb}^{-1}

should be seen within one/two year

VBF (LO) dominates over DY since couplings of q to W' are reduced

Number of events at the LHC, 300 \text{ fb}^{-1}

Christophe Grojean

Non-Standard EWSB

Birkedal, Matchev, Perelstein '05

He et al. '07

Edinburgh, February 13th 2008
Composite Higgs Models

The LHC sees the Higgs and nothing else...
**Minimal Composite Higgs Model**

Agashe, Contino, Pomarol '04

- $SO(5) \times U(1)_{B-L}$
- $SU(2)_L \times U(1)_Y$
- $SO(4) \times U(1)_{B-L}$

$\Omega = \frac{R_{IR}}{R_{UV}} \approx 10^{16}$ GeV

$z = R_{UV} \sim 1/M_{Pl}$

$z = R_{IR} \sim 1/\text{TeV}$

$A_\mu$

SO(5)/SO(4) contains a doublet

Adj

UV brane

IR brane

$ds^2 = \left( \frac{R}{z} \right)^2 (\eta_{\mu\nu} dx^\mu dx^\nu - dz^2)$

$\mathbf{SO(4)}$

$\mathbf{SO(5)}$

$\mathbf{SO(4)}$

$\mathbf{Adj}$

$A_5$
Unitarity with Composite Higgs

Technicolor: $W_L$ and $Z_L$ are part of the strong sector

Higgs = composite object (part of the strong sector too)  
its couplings deviate from a point-like scalar

Unitarity halfway between weak and strong unitarizations!

- susy: no naturalness pb  $\supset$ no need for new particles to cancel  
  $\Lambda^2$ divergences

- technicolor: heavier rho  $\supset$ smaller oblique corrections; one  
  tunable parameter: $v/f$.  

$S_{UV} \sim \frac{g^2 N \ v^2}{96 \pi^2 \ f^2}$

Christophe Grojean

Non-Standard EWSB
How to obtain a light composite Higgs?

Higgs = Pseudo-Goldstone boson of the strong sector

$m_{\text{Higgs}} = 0$ when $g_{\text{SM}} = 0$

Strong sector broadly characterized by 2 parameters

- $m_\rho$ = mass of the resonances
- $g_\rho$ = coupling of the strong sector or decay constant of strong sector

$g_{\text{SM}}$ = proto-Yukawa

$g_\rho$ = gauge

$G/H$ = residual global symmetry

UV completion

$4\pi f$ = 10 TeV

$m_\rho = g_\rho f$

usual resonances of the strong sector

$v$ = 246 GeV  

Higgs = light resonance of the strong sector

strong sector broadly characterized by 2 parameters

$m_\rho$ = mass of the resonances

$g_\rho$ = coupling of the strong sector or decay constant of strong sector

$f = \frac{m_\rho}{g_\rho}$
Testing the composite nature of the Higgs?

if LHC sees a Higgs and nothing else*:

- evidence for string landscape???
- it will be more important then ever to figure out whether the Higgs is composite!

**Model-dependent:** production of resonances at $m_{\rho}$

**Model-independent:** study of Higgs properties & W scattering

- Higgs anomalous coupling
- strong WW scattering
- strong HH production
- gauge bosons self-couplings

* a likely possibility that precision data seems to point to, at least in strongly coupled models
What distinguishes a composite Higgs?

Giudice, Grojean, Pomarol, Rattazzi '07

\[ \mathcal{L} \supset \frac{c_H}{2f^2} \partial^\mu (|H|^2) \partial_\mu (|H|^2) \quad c_H \sim O(1) \]

\[ U = e^{i \left( \frac{H^\dagger}{f} f \right)} U_0 \]

\[ f^2 \text{tr} (\partial_\mu U^\dagger \partial^\mu U) = |\partial_\mu H|^2 + \frac{\#}{f^2} (\partial |H|^2)^2 + \frac{\#}{f^2} |H|^2 |\partial H|^2 + \frac{\#}{f^2} |H^\dagger \partial H|^2 \]
What distinguishes a composite Higgs?

\[ \mathcal{L} \supset \frac{c_H}{2f^2} \partial^\mu (|H|^2) \partial_\mu (|H|^2) \quad c_H \sim \mathcal{O}(1) \]

\[ H = \begin{pmatrix} 0 \\ v + \frac{h}{\sqrt{2}} \end{pmatrix} \]

\[ \mathcal{L} = \frac{1}{2} \left( 1 + \frac{c_H v^2}{f^2} \right) (\partial^\mu h)^2 + \ldots \]

Modified Higgs propagator \( \sim \) Higgs couplings rescaled by

\[ \frac{1}{\sqrt{1 + c_H \frac{v^2}{f^2}}} \sim 1 - c_H \frac{v^2}{2f^2} \]

no exact cancellation of the growing amplitudes

unitarization restored by heavy resonances

Strong W scattering below \( m_\rho \)

Giudice, Grojean, Pomarol, Rattazzi ‘07

Falkowski, Pokorski, Roberts ‘07

Christophe Grojean

Non-Standard EWSB

Edinburgh, February 13th 2008
SILH Effective Lagrangian
(strongly-interacting light Higgs)

Giudice, Grojean, Pomarol, Rattazzi '07

extra Higgs leg: \( H/f \)

extra derivative: \( \partial/m_\rho \)

**Genuine strong operators** (sensitive to the scale \( f \))

\[
\frac{c_H}{2f^2} \left( \partial_\mu (|H|^2) \right)^2
\]

\[
\frac{c_T}{2f^2} \left( H^\dagger \overleftrightarrow{D_\mu} H \right)^2
\]

\[
\frac{c_y y_f}{f^2} |H|^2 f_L H f_R + \text{h.c.}
\]

\[
\frac{c_6 \lambda}{f^2} |H|^6
\]

**Form factor operators** (sensitive to the scale \( m_\rho \))

\[
\frac{i c_W}{2m_\rho^2} \left( H^\dagger \sigma^i \overleftrightarrow{D_\mu} H \right) (D^\nu W_{\mu\nu})^i
\]

\[
\frac{i c_B}{2m_\rho^2} \left( H^\dagger \overleftrightarrow{D_\mu} H \right) (\partial^\nu B_{\mu\nu})
\]

\[
\frac{i c_{HW}}{m_\rho^2} \frac{g_\rho^2}{16\pi^2} (D^\mu H)^\dagger \sigma^i (D^\nu H) W_{\mu\nu}^i
\]

\[
\frac{i c_{HB}}{m_\rho^2} \frac{g_\rho^2}{16\pi^2} (D^\mu H)^\dagger (D^\nu H) B_{\mu\nu}
\]

\[
\frac{c_\gamma}{m_\rho^2} \frac{g_\rho^2}{16\pi^2} H^\dagger H B_{\mu\nu} B^{\mu\nu}
\]

\[
\frac{c_g}{m_\rho^2} \frac{g_\rho^2}{16\pi^2} \frac{y_t^2}{g^2_\rho} H^\dagger H G_{\mu\nu}^a G^{a\mu\nu}
\]

minimal coupling: \( h \to \gamma Z \)

Goldstone sym.

loop-suppressed strong dynamics

Christophe Grojean

Non-Standard EWSB

Edinburgh, February 13th 2008
**EWPT constraints**

\[ \hat{T} = c_T \frac{v^2}{f^2} \quad \Rightarrow \quad \left| c_T \frac{v^2}{f^2} \right| < 2 \times 10^{-3} \]

\[ \hat{S} = (c_W + c_B) \frac{m_W^2}{m_\rho^2} \quad \Rightarrow \quad m_\rho \geq (c_W + c_B)^{1/2} \quad 2.5 \text{ TeV} \]

removed by custodial symmetry

There are also some 1-loop IR effects

Barbieri, Bellazzini, Rychkov, Varagnolo '07

\[ \hat{S}, \hat{T} = a \log m_h + b \]

modified Higgs couplings to matter

\[ \hat{S}, \hat{T} = a \left( (1 - c_H \xi) \log m_h + c_H \xi \log \Lambda \right) + b \]

effective Higgs mass

\[ m_{h}^{\text{eff}} = m_h \left( \frac{\Lambda}{m_h} \right)^{c_H v^2/f^2} > m_h \]

LEPII, for \( m_h \sim 115 \text{ GeV} \):

\[ c_H v^2/f^2 < 1/3 \sim 1/2 \]

IR effects can be cancelled by heavy fermions (model dependent)
Higgs anomalous couplings

\[ \Gamma(h \rightarrow f \bar{f})_{\text{SILH}} = \Gamma(h \rightarrow f \bar{f})_{\text{SM}} \left[ 1 - (2c_y + c_H) \frac{v^2}{f^2} \right] \]

\[ \Gamma(h \rightarrow gg)_{\text{SILH}} = \Gamma(h \rightarrow gg)_{\text{SM}} \left[ 1 - (2c_y + c_H) \frac{v^2}{f^2} \right] \]

observable @ LHC?

LHC can measure

\[ c_H \frac{v^2}{f^2} = 1/4 \]
\[ c_y \frac{v^2}{f^2} = 1/4 \]

(observable up to 20-40%)

(composite scale 5-7 TeV)

(ILC could go to few %)

ie test composite Higgs up to \[ 4\pi f \sim 30 \text{ TeV} \]
Strong W scattering

Even with a light Higgs, growing amplitudes (at least up to $m_\rho$)

$$
\mathcal{A} (Z_L^0 Z_L^0 \rightarrow W_L^+ W_L^-) = \mathcal{A} (W_L^+ W_L^- \rightarrow Z_L^0 Z_L^0) = -\mathcal{A} (W_L^\pm W_L^\pm \rightarrow W_L^\pm W_L^\pm) = \frac{c_H s}{f^2}
$$

$$
\mathcal{A} (W^\pm Z_L^0 \rightarrow W^\pm Z_L^0) = \frac{c_H t}{f^2}, \quad \mathcal{A} (W_L^+ W_L^- \rightarrow W_L^+ W_L^-) = \frac{c_H (s + t)}{f^2}
$$

$$
\mathcal{A} (Z_L^0 Z_L^0 \rightarrow Z_L^0 Z_L^0) = 0
$$

leptonic vector decay channels
forward jet-tag, back-to-back lepton, central jet-veto
with 300 fb$^{-1}$
30 signal-events and 10 background-events

Bagger et al '95
Butterworth et al. '02

LHC is sensitive to
$$\frac{v^2}{c_H f^2}$$
bigger than
$0.5 \sim 0.7$
Strong Higgs production

O(4) symmetry between $W_L$, $Z_L$ and the physical Higgs

strong boson scattering $\Leftrightarrow$ strong Higgs production

$$A\left(Z^0_L Z^0_L \rightarrow hh\right) = A\left(W^+_L W^-_L \rightarrow hh\right) = \frac{c_H s}{f^2}$$

signal: $\bullet$ hh $\rightarrow$ bbbb

$\bullet$ hh $\rightarrow$ 4W $\rightarrow$ $\ell^+\ell^-\nu\nu$ jets

Sum rule (with cuts $|\Delta\eta| < \delta$ and $s < M^2$)

$$2\sigma_{\delta,M} (pp \rightarrow hhX)_{c_H} = \sigma_{\delta,M} (pp \rightarrow W^+_L W^-_L X)_{c_H} + \frac{1}{6} \left( 9 - \tanh^2 \frac{\delta}{2} \right) \sigma_{\delta,M} (pp \rightarrow Z^0_L Z^0_L X)_{c_H}$$
Direct vs. indirect signals

direct production of (TeV) resonances

\begin{align*}
q \rightarrow \rho & = \frac{g_{SM}^2}{g_{\rho}} \\
\sigma (pp \rightarrow \rho_H^\pm + X) & = \left( \frac{4\pi}{g_{\rho}} \right)^2 \left( \frac{3 \text{ TeV}}{m_\rho} \right)^6 0.5 \text{ fb}
\end{align*}

for larger $g_{\rho}$, the resonances are increasingly harder to see as
1/ they are broader and heavier
2/ they couple more and more weakly to fermions

LHC could reach a resonance around 4 TeV
Continuous Connections between Models

Composite Higgs → Higgsless

reduce couplings Higgs/W,Z

“gaugephobic higgs”

new realization of old
✓ bosonic technicolor
✓ topcolor assisted technicolor

Cacciapaglia, Csaki, Marandella, Terning ‘06

Carone, Simmons ‘92

Hill ‘94
Exotic Scenarios

The LHC see many exciting signatures beyond the Standard Model...
Hidden valley models

- low mass hidden sectors connected to SM through higher dimension operators
- hidden = neutral under SM gauge group, charged under high mass mediator
- possible decays to ‘our’ universe via tunneling

Strassler, Zurek ’06
To complete the review...

- **Unparticles**
  
  - example of hidden valley models with a hidden sector with a non-trivial conformal IR fixed point
  
  - unparticles look like a non-integral number of invisible particles

- **Higgs portal**

  - more Higgs doublets or new Higgs singlets
  
  - dark matter candidates
  
  - strengthen the EW phase transition $\Rightarrow$ EW baryogenesis

---

- Patt, Wilczek ’06, Chang, Fox, Weiner ’05, O’Connel, Ramsey-Musolf, Wise ’06, Espinosa, Quiros ’07 +...
Conclusions

EW interactions need a UV moderator to unitarize WW scattering amplitude

"theorists are getting cold feet"  J. Ellis
"they have done their best to predict the possible and impossible"  G. Giudice

Oblique corrections are a test of new physics

Need other observables to identify the nature of new physics
What is the mechanism of EW symmetry breaking?

1/ is there a Higgs? ✓ ✓ ✓
2/ what are the Higgs mass/couplings ✓/− ✓ ✓
3/ is the Higgs a SM like weak doublet? 
4/ is the Higgs elementary or composite? 
5/ is EWSB natural or fine-tuned? ✓ ✓ ✓
6/ are there new dimensions? new strong forces? − ✓ ✓