What lies beyond?

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A theorist's view on the problems and perspectives of particle physics beyond the standard model

general principles $\longrightarrow$ facts

What are the smallest constituents of matter, the “elementary” particles?

The notion itself has evolved over time from “earth, water & fire...” to the current “standard model” of elementary particle physics.

Our major motivation is finding the organizing principles, rather than “smaller is better”!

Our current understanding of the "elementary constituents" of "everything" is based on a powerful organizing principle, which found its origin in the rather abstract work of Yang and Mills in the 1950s:

NONABELIAN GAUGE INVARIANCE

based on this principle, the "standard model" of elementary particle physics has, since the 1970s, unified three of the fundamental forces

the "standard model"...

has unified electromagnetism with the weak interactions and given us a theory of the strong force...

is in unprecedented agreement with experiment...

K. Hagiwara *et al.*, Phys. Rev. D **66**, 010001 (2002)

$\mu = 1.001159652187 \pm 0.000000000004\ \mu_B$

			experiment	theory	
M_Z	[GeV]	LEP	91.1876 ± 0.0021	91.1874 ± 0.0021	0.1
Γ_Z	[GeV]	LEP	2.4952 ± 0.0023	2.4972 ± 0.0011	−0.9
$\Gamma(\text{inv})$	[MeV]	LEP	499.0 ± 1.5	501.74 ± 0.15	—
σ_{had}	[nb]	LEP	41.541 ± 0.037	41.470 ± 0.010	1.9
R_e		LEP	20.804 ± 0.050	20.753 ± 0.012	1.0
R_μ		LEP	20.785 ± 0.033	20.753 ± 0.012	1.0
R_τ		LEP	20.764 ± 0.045	20.799 ± 0.012	−0.8
R_b		LEP + SLD	0.21644 ± 0.00065	0.21572 ± 0.00015	1.1
R_c		LEP + SLD	0.1718 ± 0.0031	0.17231 ± 0.00006	−0.2
$A_{FB}(b)$		LEP	0.0995 ± 0.0017	0.1036 ± 0.0008	−2.4
$A_{FB}(c)$		LEP	0.0713 ± 0.0036	0.0741 ± 0.0007	−0.8
A_b		SLD	0.922 ± 0.020	0.93477 ± 0.00012	−0.6
A_c		SLD	0.670 ± 0.026	0.6681 ± 0.0005	0.1
A_{LR} (hadrons)		SLD	0.15138 ± 0.00216	0.1478 ± 0.0012	1.6

J. Erler and P. Langacker

available on the PDG WWW pages (URL: http://pdg.lbl.gov/) June 18, 2002

...the list goes on...

the standard model's success is an example of a

good theory:

starting from first principles, one arrives(*) at a theory of the quarks' and leptons' interactions via gauge forces

(*) "some" experimental input is required...

Herman Weyl, 1929:

..."equivalence principle" in "charge" space....

postulate:

physics is independent of space- and time-dependent (i.e. "local") phase transformations

$$\Psi(x) \rightarrow e^{i\alpha(x)}\ \Psi(x)$$

phase of wave function

the gauge equivalence principle, like Einstein's equivalence principle in general relativity, leads to the appearance of new dynamical degrees of freedom:

the gauge fields

$$\Psi(x) \rightarrow e^{i\alpha(x)}\,\Psi(x)$$

$$\frac{\partial}{\partial x}\Psi(x) \rightarrow e^{i\alpha(x)}\frac{\partial}{\partial x}\Psi(x) + e^{i\alpha(x)}\,i\,\frac{\partial\alpha}{\partial x}\,\Psi(x)$$

trouble: Schroedinger equation [physics] depends on local phase covariant derivative

$$\frac{\partial}{\partial x} \rightarrow \frac{\partial}{\partial x} + i\ A_x(x)$$

$$A_x(x) \rightarrow A_x(x) + \frac{\partial \alpha}{\partial x}$$

the x-component of the "gauge field" A

Maxwell's electromagnetic field appears due to the gauge equivalence principle

Maxwell's theory is an example of an Abelian gauge field theory

Think of the gauge transformations as of elements of a group - in this case, U(1):

$$x \rightarrow e^{i\alpha(x)}$$

$$e^{i\alpha_1(x)} \cdot e^{i\alpha_2(x)} = e^{i(\alpha_1(x)+\alpha_2(x))}$$

A * B = (AB)

B * A = (BA) = (AB) = A * B

Abelian = gauge transformations commute

C.N. Yang and R. Mills, in 1954, considered a generalization of the gauge equivalence principle to non-commuting groups - non-Abelian gauge field theory

if the wave function is a multicomponent one, i.e. charge space is more than one (complex) dimensional:

$$\begin{pmatrix} \Psi_1(x) \\ \Psi_2(x) \end{pmatrix} \rightarrow U(x) \begin{pmatrix} \Psi_1(x) \\ \Psi_2(x) \end{pmatrix}$$

U(x) is now a unitary 2x2 matrix, an element of SU(2) "gauge group"

This rather abstract construction laid the foundation of modern particle theory.

Many "details"...

quantization, "renormalizability"...

Feynman, Faddeev, Popov, 't Hooft, Veltman...

incorporating massive gauge bosons...

Nambu, Higgs...

discovery of "asymptotic freedom"...

Gross, Wilczek, Politzer...

A note of caution:

the gauge equivalence principle
does not completely determine the theory

what is the “gauge group” G?

any compact Lie group is OK...
U(1), SU(n), SO(n), SP(n), G2, F4, E6, E8; ...and products thereof!

what is the dimensionality of the “charge space”?

i.e. what “representation” of G do the wave functions of the various particles transform in...
there exist a few theoretical consistency constraints, but not nearly enough...

so, proceed by trial and error and comparison with experiment (“model building”)... 1969-72

The outcome is a nice theory, describing the interactions of:

Weinberg, Salam, Glashow

Spin-1/2 fermions

quarks

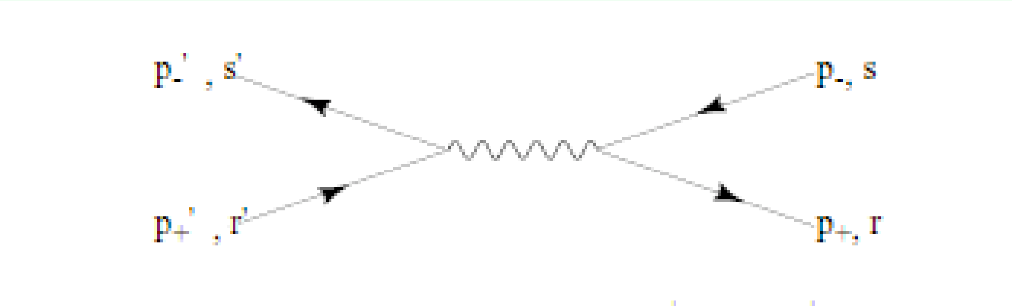
$$\begin{matrix} u & s & b \\ d & c & t \end{matrix}$$

leptons

$$\begin{matrix} e & \mu & \tau \\ \nu_e & \nu_\mu & \nu_\tau \end{matrix}$$

with Spin-1 gauge bosons

photon — W and Z bosons — gluons



Feynman diagram contributing to $e^+e^- \to \mu^+\mu^-$

This "nice" theory, in addition to agreeing with experiment, also predicted the existence of the top (t) quark, **found in 1996 at Fermilab.**

It is fair to say that the development of non-abelian gauge theories and the standard model is one of the greatest achievements of 20th century physics!

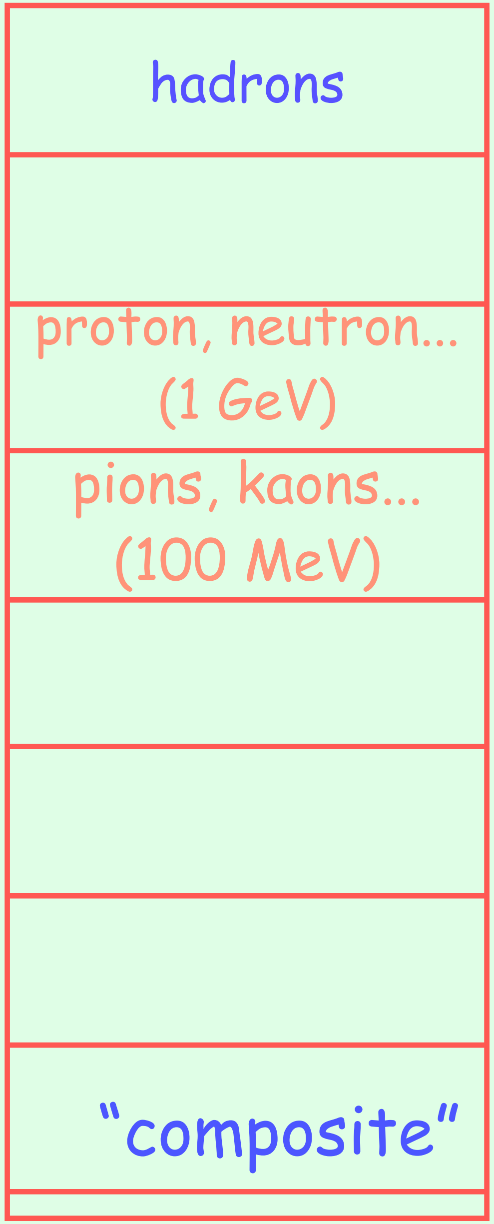
However, let us now take a look at some experimental "detail"...

Energy scale	gauge bosons	leptons	quarks	hadrons
100 GeV	W, Z (81-90 GeV)		top (174 GeV)	
1 GeV		tau	bottom, charm	proton, neutron, lambda, delta...
100 MeV		muon (105 MeV)	strange	pions, kaons...
1 MeV		electron (500 keV)	up, down (a few MeV)	
1 meV		neutrinos		
0 eV	photon, gluon (graviton)			
	"elementary"			"composite"

The SU(3)xSU(2)xU(1) gauge bosons are the gluons, electroweak W,Z bosons, and the photon.

appearance ("emergence") of hadrons at the 1 GeV scale is due to confinement of "color" in quantum chromodynamics (QCD), the nonabelian gauge theory of strong interactions

not an unfamiliar situation in theoretical physics: know theory but can't solve - i.e. strongly-correlated electrons; lattice gauge theories studies important.



illustrates generic feature:

nonabelian gauge theories lead to strong interactions at large distances

...coming back to our "elementary" particles...

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	"elementary"		

"amazing": standard model works from 1 meV to 100 GeV

12 orders of magnitude difference in energy scale!

on the other hand... we don't really understand this spectrum!

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Three "generations" of quarks and leptons: Who ordered them?

the masses of W, Z, quarks, and leptons are FREE parameters, spanning 14 orders of magnitude!

This is drastically different from "everyday" physics (atomic, solid state...)

If this sounds bad, recall that only three of the four fundamental interactions are unified within the standard model...

remember GRAVITY!

customarily, particle physicists treat gravity classically, doing (at best) quantum field theory in a fixed curved background

Is there a need to improve on this... why bother?

after all $$M_{Planck} = \sqrt{\frac{\hbar c}{G_N}} = 1.2 \times 10^{19} GeV$$

while $$M_{W^\pm, Z} \simeq 10^2 GeV$$

so for any current (and future!) experiments quantum gravity effects can be safely ignored

Well, quantum gravity is a noble goal...

general relativity predicts space-time singularities...

Most worrysome, even when simply coupled to classical gravity, the standard model does really badly. The standard model coupled to the model of the expanding universe (Freedman-Robertson-Walker) "predicts" that the universe expands 15 to 30 orders of magnitude faster than is observed.

(note the error bars)

This problem, known as the cosmological constant problem is the most serious flaw of our current "Wilsonian" description of physics at energies below 100 GeV (or so).

A related (perhaps) problem is that of explaining the "weakness" of the weak interactions (and all the other, nongravitational ones) compared to the strength of gravity:

$$G_{Fermi} \simeq \frac{1}{M_W^2} \simeq \frac{1}{10^4 GeV^2}$$

$$\frac{G_{Fermi}}{G_{Newton}} \simeq 10^{-34}$$

$$G_{Newton} \simeq \frac{1}{M_{Planck}^2} = \frac{1}{10^{38} GeV^2}$$

$$\frac{G_{Fermi}}{G_{Newton}} \simeq 10^{-34}$$

ratio is usually expressed as a ratio of mass scales, that of the W-boson to the Planck scale, and is of order 10^{-17}

The difficulty we have comprehending such a small ratio of scales is usually referred to as the "gauge hierarchy problem."

We currently have more ideas of how to explain this small ratio than of how to solve the cosmological constant problem.

The origin of the Fermi constant has to do with the mechanism that is responsible for "generating" the masses of all elementary particles.

(why do W, Z masses need to be "generated"?)

...massive gauge bosons' scattering amplitudes violate unitarity...

A massless gauge boson - photon - has two polarizations [helicities: S_p= 1, -1].

A massive gauge boson - W,Z - has three [S_z= 1, 0, -1].

If the photon had some small mass m, the interactions of its S_z= 0 polarization state would violate unitarity at energies m/e.

Therefore, some other dynamics should occur at that scale to restore the consistency of the theory.

...in essence, some mechanism of "mass generation" is required to restore the conservation of probability...

We know an example: superconductivity. The photon is massless, of course, but acquires a “longitudinal” polarization because of its interaction with the medium.

We think that the W, Z mass is due to a Meissner-type effect, the “Higgs mechanism” (Anderson, Kibble, Nambu, Higgs...)

A Bose condensate of charged particles (Cooper pairs) in a superconductor generates a mass for the photon (the inverse of the London penetration depth): magnetic fields are expelled and penetrate only a layer near the boundary of the superconductor

...one catch: presently, we do not know the nature of the condensate giving rise to W, Z masses!

...to be unravelled at the Large Hadron Collider at CERN (Geneva, Switzerland) after 2007...

... the condensate may be

a fundamental scalar field: the Higgs particle

supersymmetry (SUSY)

predicts superpartners of all ordinary particles: selectron, photino...

a composite, Cooper pair like object

technicolor

predicts technihadrons and other "emergent" strong dynamics

currently favored by experimentalist and phenomenologists: they are easier to deal with (weak coupling!)... but watch out...

...to be unravelled at the Large Hadron Collider at CERN (Geneva, Switzerland) after 2007...

Will not dwell in details. The big picture is that we have ideas how the masses of W, Z bosons and all the rest can be generated.

These ideas are testable in the near future.

Moreover, we also know a mechanism explaining the small ratio of the electroweak and Planck scales.

Borrowed from condensed matter physics, goes under the name of "dynamical (super-)symmetry breaking."

The idea is, essentially, that a small coupling can give rise to a large - even exponential - hierarchy of mass scales.

the mass of the photon in a superconductor is proportional to the gap:

$$\Delta = \hbar\omega_{Debye}\, e^{-\frac{2}{g\nu(\epsilon_F)}}$$

electron-phonon coupling

the maximum energy of phonons, the “UV cutoff” of the theory

Now we taylor this expression to elementary particle physics:

$$\omega_{Debye} \to M_{Planck}$$

electron-phonon coupling → coupling constant in theory responsible for symmetry breaking

photon mass (gap) → mass of W, Z bosons **or** mass of superpartners

So, we arrive at the conclusion that DYNAMICAL (SUPER-) SYMMETRY BREAKING can generate exponentially small scales, e.g.:

$$m_W \simeq M_{Planck}\, e^{-\frac{\mathcal{O}(1)}{g^2}}$$

The "THIS IS IT!" model not there yet...

Mechanisms described up to now all involve NONABELIAN GAUGE THEORIES, beyond the SU(3)xSU(2)xU(1) gauge theory of the standard model.

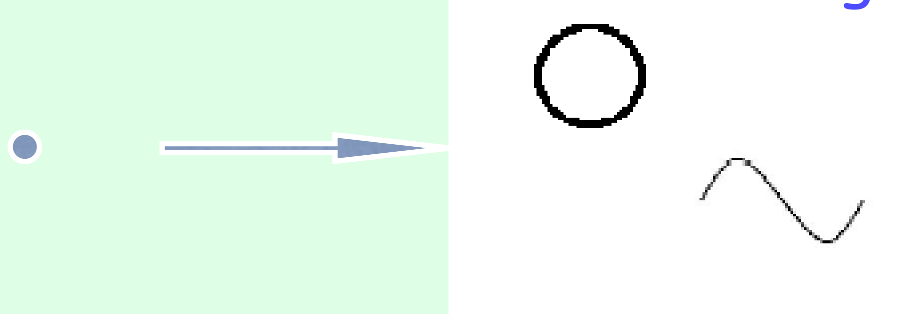
In many cases at strong coupling - far from solved! (...)

Meanwhile, while waiting for new experimental data, theorists are busy...

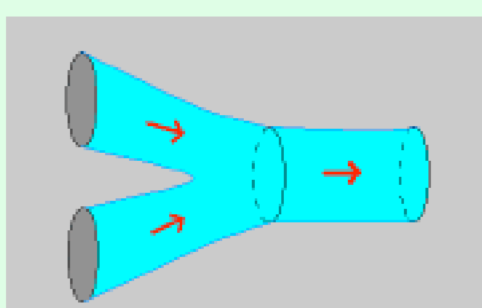
... a different first principles approach is offered by string theory [1969 - 1984 - 1994 - milestone years]

It turns out that replacing point particles with strings is a very promising direction!

closed strings: gravity



open strings: gauge theory



intimately related: perhaps, a true unification?

In recent years [1997-] we have witnessed the beginning of a synthesis of these approaches.

nonabelian gauge theory ↔ (quantum dualities) ↔ string theory

Some string theories at weak coupling describe, in fact, the strong coupling limits of gauge field theories; perhaps they are the same and in fact gravity = gauge theory!

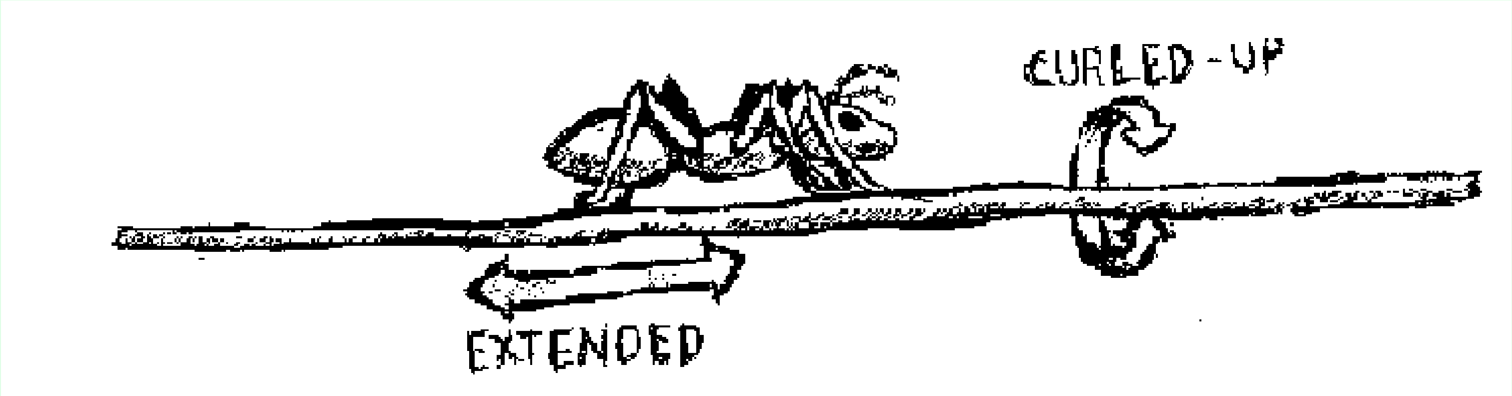
These dualities give us a new handle on (supersymmetric) strong-coupling gauge theory dynamics.

...Polyakov, Maldacena, Witten-Gubser-Klebanov, 1998-99

Apart from the purely intellectual appeal, these developments also led to new approaches to the gauge hierarchy problem [i.e., new ideas how to generate exponentially small scales].

In particular, the idea of large extra dimensions was one of the main consequences of string theory developments.

Old idea....

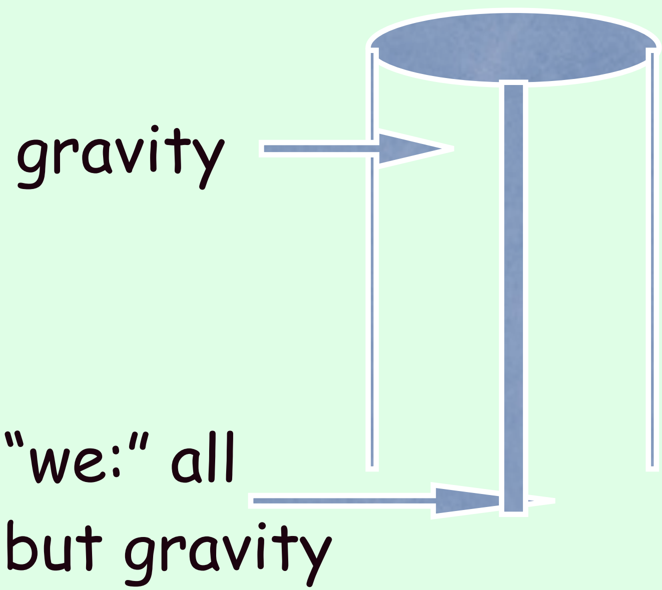


Kaluza; Klein, 1920s

New twist: large extra dimensions

Arkani-Hamed, Dimopolous, Dvali, 1998

Imagine that we live on a "defect" in some extra dimensions: "braneworld scenario," micron-size [="large"] dimensions.

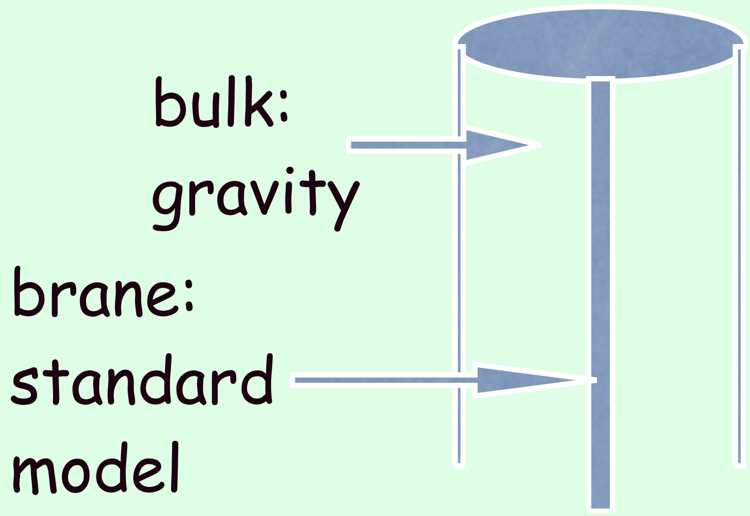


Large size only allowed (by experiment) if non-gravitational interactions are confined to a "brane."

String theory allows for such a "confining" mechanism.

In this scenario, classical gravity description "ends" at an energy scale comparable to the electroweak scale (~TeV):

the higher dimensional G_{Newton} is of the same order as G_{Fermi} , but "we" [on the brane, in 3+1 dim] feel a gravity flux diluted by the extra micron-size dimensions. Two micron-size extra dimensions accomodate a 6dim. G_{Newton} of order TeV.



Picture is consistent with all experimental data; moreover, precision gravity experiments on micron-size distances can see predicted deviations from Newton's law...

review: E. Adelberger et al, 12/2003.

Reformulates gauge hierarchy problem: **not issue of Fermi to Newton constant ratio, but that of why size of the extra dimension is so large compared to the Compton wavelength of the W, Z bosons: 1 vs. 10^{-16} microns.**

The theory is in its infancy; mostly toy models, so far.

Other interesting scenarios exploiting extra dimensions to address gauge hierarchy problem also exist... Randall, Sundrum, 1999

Standard model works great, so far (E < 100 GeV).

Many puzzles left.

But we've got some ideas:

Mature:

technicolor and supersymmetry, exploiting nonabelian gauge dynamics to address physics beyond the standard model.

Young:

extra dimensions, branes, and strings in physics beyond the standard model.

With the advent of the Large Hadron Collider we should learn more of what lies beyond the electroweak symmetry breaking and the gauge hierarchy problem... stay tuned 2008 +

The novel (”young”) theoretical ideas of electroweak (TeV) scale physics also offer hope that we might be able to tell whether string theory will become the GOOD THEORY of the 21st century!

Questions?