Varying fundamental constants and particle physics

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Overview

- The general idea
- Old idea: Varying electromagnetic coupling
- Particle physics → new scalar particles
- Generalization to SU(3) × SU(2) × U(1)
- Generalization to Yukawa couplings
- Collider signatures

All results in this talk are based on work with Ulf Danielsson, Gunnar Ingelman, Tanumoy Mandal: arXiv:1601.00624 (Nucl. Phys. B, in press) and a forthcoming paper

Free parameters of the SM

Fundamental constant: ***a parameter that cannot be explained by the theory*** *(even in principle)*

How many parameters are there in the Standard Model?

- 19: Yukawas, gauge couplings, CKM, theta, Higgs
- 26: If we include neutrino mixing and masses
- 27: If we include the cosmological constant
- 31–37: If we add cosmological standard model
  [See e.g. Tegmark et al., PRD 73 (2006) 023505]

And then there are c, ħ, G, k_B, etc. …

Recommended reading:

R.N. Cahn, Rev. Mod. Phys. **68** (1996) 951-960
M.J. Duff, arXiv:1412.2040

From Wikipedia, "Standard Model"

Parameters of the Standard Model			[hide]
Symbol	**Description**	**Renormalization scheme (point)**	**Value**
m_e	Electron mass		511 keV
m_μ	Muon mass		105.7 MeV
m_τ	Tau mass		1.78 GeV
m_u	Up quark mass	$\mu_{\overline{MS}} = 2$ GeV	1.9 MeV
m_d	Down quark mass	$\mu_{\overline{MS}} = 2$ GeV	4.4 MeV
m_s	Strange quark mass	$\mu_{\overline{MS}} = 2$ GeV	87 MeV
m_c	Charm quark mass	$\mu_{\overline{MS}} = m_c$	1.32 GeV
m_b	Bottom quark mass	$\mu_{\overline{MS}} = m_b$	4.24 GeV
m_t	Top quark mass	On-shell scheme	172.7 GeV
θ_{12}	CKM 12-mixing angle		13.1°
θ_{23}	CKM 23-mixing angle		2.4°
θ_{13}	CKM 13-mixing angle		0.2°
δ	CKM CP-violating Phase		0.995
g_1 or g'	U(1) gauge coupling	$\mu_{\overline{MS}} = m_Z$	0.357
g_2 or g	SU(2) gauge coupling	$\mu_{\overline{MS}} = m_Z$	0.652
g_3 or g_s	SU(3) gauge coupling	$\mu_{\overline{MS}} = m_Z$	1.221
θ_{QCD}	QCD vacuum angle		~0
v	Higgs vacuum expectation value		246 GeV
m_H	Higgs mass		125.36 ±0.41 GeV (tentative)

What are the fundamental constants and what are just units?

- There's a debate in the literature about what are the fundamental constants, and how many are there. [e.g. Duff, Okun. Veneziano, arXiv:physics/0110060]
- Michael Duff in particular argues that only dimensionless constants are fundamental. Dimensionful constants are just unit conversions *(Fathoms and nautical miles)*

speed of light = 1 lightyear/year

- *"Asking whether c has varied over cosmic history … is like asking whether the number of litres to the gallon has varied"* [M.J. Duff, arXiv:1412.2040]

Varying coupling constants?

- Coupling "constants" vary with energy scales as given by the renormalization group: this is normal QFT and not what I mean here
- But they might also vary as functions of $x^\mu = (t,x,y,z)$
- Consistent if they are given by ***dynamical fields***
- Old idea (Dirac 1937, Jordan 1937, …). **Bekenstein** proposed a simple consistent model in 1982
- Varying fundamental constants have been explored in various contexts in cosmology
- Review: J.-P. Uzan, "*Varying Constants, Gravitation and Cosmology*", Living Rev. Relativity **14** (2011) 2

String theory

In string theory there are no free parameters
— all parameters are set by VEVs of scalar fields

Find correct compactification → constants predicted

These scalar fields are called ***moduli fields***

The modulus field that sets the string coupling g_s is called the ***dilaton*** S. In e.g. heterotic string theory

$$S = V_6 e^{-2\phi} + ia$$

where V_6 depends on the compactification, a is an axion. The string coupling is then

$$g_s = e^{\phi}$$

String theory

The point is that

All fundamental constants are VEVs of moduli fields

These constants are not freely adjustable – they are dynamical parameters → can be calc. from a potential

If these scalars have eqs. of motion that allow the VEVs to vary over spacetime → **constants can vary**

If VEVs frozen at some scale, constants are constant below that scale but may vary at higher scales

Couplings as fields

Lorentz invariance → the fields must be scalars

Very natural idea: once you find the correct theory (e.g. a string compactification)

→ All parameters are predicted

- All parameters are locked at their values as long as the scalar field is at its minimum
- If the field is excited, the parameters are not fixed
- Alternatively, scalar particles appear

Particle physics

Many concepts have previously been borrowed from string theory and used in particle physics:

- Supersymmetry
- Extra dimensions
- Branes
- …

Now we would like to borrow the concept of moduli fields and dynamical couplings

But we are not doing string phenomenology here!

Bounds on coupling variations

Bounds on $\Delta\alpha/\alpha$ from:

- Big Bang Nucleosynthesis
- Cosmic Microwave Background
- Oklo reactor [natural reactor 1.8 Gyr ago in Gabon]
  (Neutron capture cross section on ^{149}Sm very sensitive to approx. cancellation of EM and strong force)
- Atomic clocks
- Quasar spectra
- Meteorite dating
- Stars, neutron stars, …

Bounds on coupling variations

All these bounds put limits on models where the parameters vary on a low energy scale: the scalar fields are massless or very light

With dynamical fields on a high mass scale, the variations would only appear at high energies

At lower energies, the parameter values are locked at the observed values

The Bekenstein model for a varying α_{EM}

In 1982 Jacob Bekenstein proposed the simplest consistent model for a varying α_{EM}, where

$$e(x) = e_0 \varepsilon(x)$$

$\varepsilon(x)$ replaces the constant coupling (we extract the vev e_0)
e_0 is the vev = the standard value for the electric charge

$\varepsilon(x)$ is a scalar field with kinetic term $\frac{1}{2}\frac{\Lambda^2}{\varepsilon^2}(\partial_\mu \varepsilon)^2$

This does not look like what we are used to for scalars!

- Invariant under rescaling of $\varepsilon(x)$
- Typically what kinetic terms for moduli look like in string theory

The Bekenstein model for a varying α_{EM}

In Bekenstein's model, the EM field strength tensor is modified to

$$\widehat{F}_{\mu\nu} = \frac{1}{\varepsilon}\left[\partial_\mu(\varepsilon A_\nu) - \partial_\nu(\varepsilon A_\mu)\right]$$

with gauge transformation $\varepsilon A_\mu \to \varepsilon A_\mu + \partial_\mu \alpha(x)$

ε(x) is dimensionless with non-standard kinetic term. Define

$$\varepsilon = e^{\varphi} \text{ with } \varphi(x) = \ln\frac{e}{e_0} \text{ and rescaling } \varphi = \phi/\Lambda$$

and expand $\varepsilon = e^{\varphi} \simeq 1 + \varphi = 1 + \phi/\Lambda$

so that we get the canonical kinetic term with standard mass dimension of ϕ(x): $\frac{1}{2}(\partial_\mu \phi)^2$

The Bekenstein model for a varying α_{EM}

In effect, everywhere: $eA_\mu \to e_0 \varepsilon A_\mu \simeq e_0(1+\phi/\Lambda)A_\mu$

For example $\widehat{D}_\mu = \partial_\mu - ie_0 Q A_\mu - \frac{ie_0 Q}{\Lambda}\phi A_\mu$

This leads to:

$$\mathcal{L} = \mathcal{L}_{\rm SM} + \frac{1}{2}(\partial_\mu \phi)^2 - \frac{1}{2}m^2\phi^2 - \frac{1}{\Lambda}\partial_\mu\phi\, A_\nu F^{\mu\nu} + \frac{e_0 Q}{\Lambda}\phi\,\overline{\psi}\gamma^\mu\psi\, A_\mu$$

where we added a mass term for the scalar.

Here everything is rewritten in terms of the **ordinary** gauge field $F_{\mu\nu}$ and EM charge e_0 **which does not vary**

Variation swapped for the existence of a scalar particle!

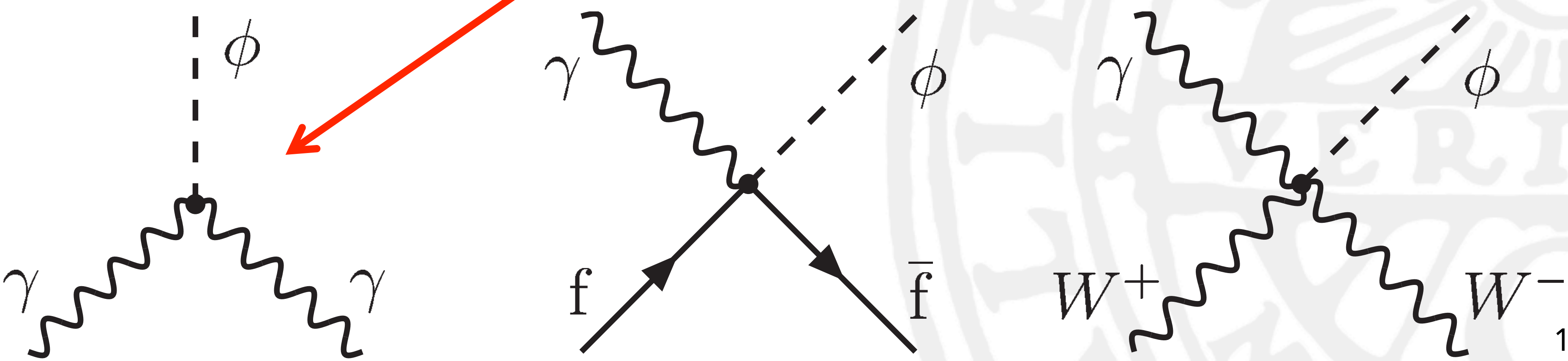
Scalar is inserted into every QED vertex with a photon

The Bekenstein model for a varying α_{EM}

$$\mathcal{L} = \mathcal{L}_{\rm SM} + \frac{1}{2}(\partial_\mu \phi)^2 - \frac{1}{2} m^2 \phi^2 - \frac{1}{\Lambda} \partial_\mu \phi \, A_\nu F^{\mu\nu} + \frac{e_0 Q}{\Lambda} \phi \, \overline{\psi} \gamma^\mu \psi \, A_\mu$$

Scalar is inserted into every QED vertex with a photon!

What are the interactions?



Alternative form of the model

The funny-looking interaction term can be integrated by parts:

$$-\frac{1}{\Lambda}\partial_\mu\phi\, A_\nu F^{\mu\nu} \to -\frac{1}{\Lambda}\phi A_\nu \partial_\mu F^{\mu\nu} + \frac{1}{2\Lambda}\phi F_{\mu\nu}F^{\mu\nu}$$

Note the Maxwell eq. $\partial_\mu F^{\mu\nu} = j^\nu = e_0\bar{\psi}\gamma^\nu\psi$

→ Use operator identity to eliminate $\frac{e_0 Q}{\Lambda}\phi\,\overline{\psi}\gamma^\mu\psi\, A_\mu$

➔ Equivalent model with ϕF^2 interaction and no direct coupling of the scalar to fermions

➔ Looks more like a "normal" new scalar

But is this the same theory?

- It's straightforward to show using Feynman diagrams that any amplitudes squared with external on-shell photons are identical in the two versions of the model
- Less clear what happens with loops
- Operator identity (e.o.m.) $\partial_\mu F^{\mu\nu} = j^\nu = e_0 \bar{\psi} \gamma^\nu \psi$ means you get theories that may have different forms and different fields, but give same S-matrix elements, at least at leading order (e.g. Politzer 1980, Arzt 1995)

→ field redefinition invariance of path integral

Summary & outlook

- Dynamical couplings given by fields with no free parameters is a natural idea in UV completions
- Leads to the existence of (potentially) many new scalar fields
- Interesting phenomenology
- How light can they be?
- Cosmology? Astrophysics? Phase transitions?