Varying couplings from scalar fields

Rikard Enberg

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All results in this talk are based on work with Ulf Danielsson, Gunnar Ingelman, Tanumoy Mandal: arXiv:1601.00624 and forthcoming paper

UPPSALA UNIVERSITET

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Non Minimal Higgs

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

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.

- Michael Duff in particular argues that only dimensionless constants are fundamental (the α's). 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: 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 (in principle) be calculated 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

We have borrowed concepts from string theory before

Bounds on EM 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 a simple consistent model for a varying α_{EM}, where

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

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

ε(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 ε(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 charge vev e_0 **which does not vary**

Variation swapped for the existence of a scalar particle!

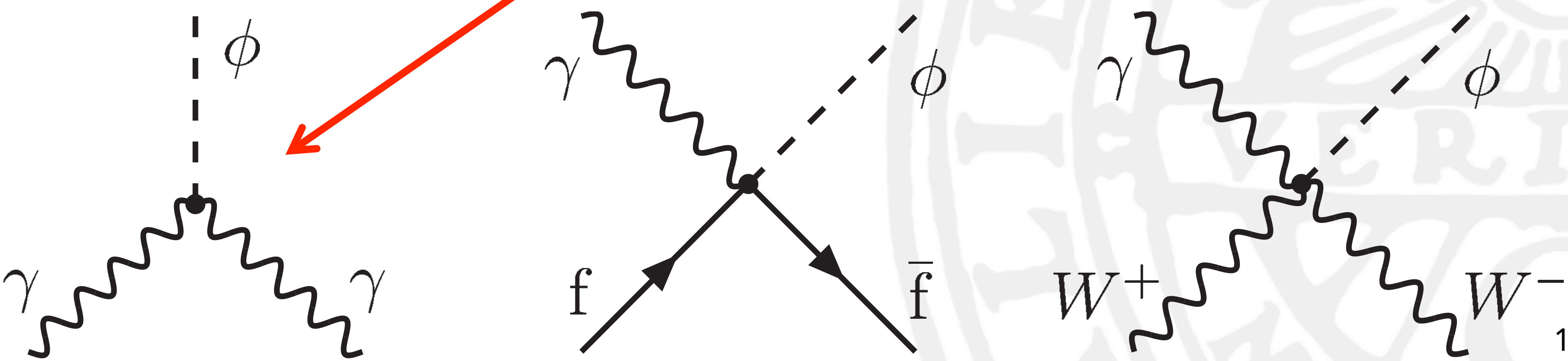
Scalar is inserted into every QED vertex with a photon

The Bekenstein model for a varying α_{EM}

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

Scalar is inserted into every QED vertex with a photon!

What are the interactions?



Alternative form of the model

Integrate the funny-looking interaction term by parts:

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

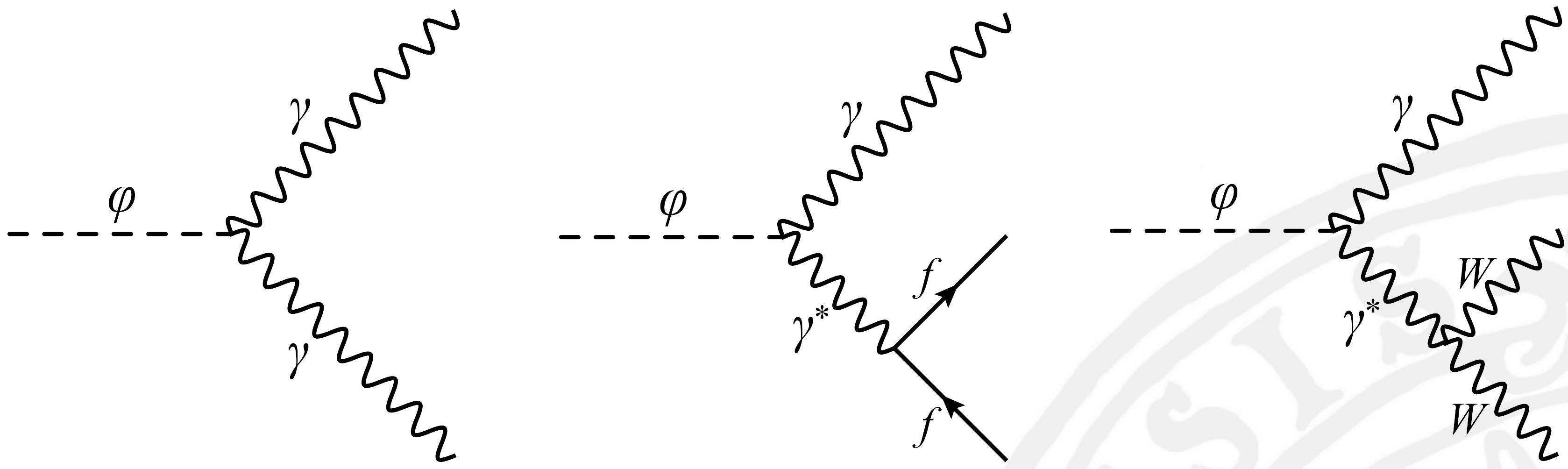
Note the Maxwell eq. $\partial_\mu F^{\mu\nu} = j^\nu = e_0\bar{\psi}\gamma^\nu\psi$

→ 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 (field redefinition)

➔ Looks more like a "normal" new scalar

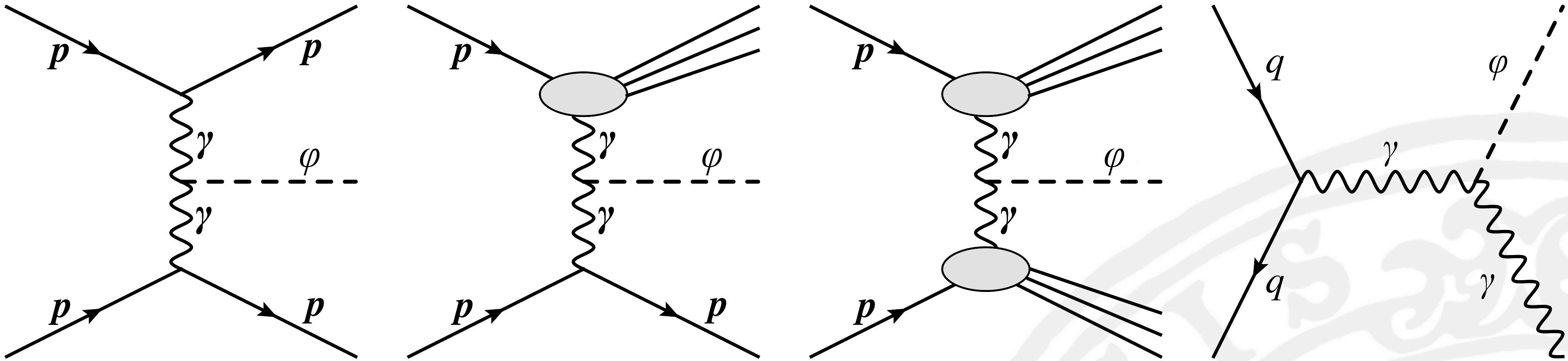
Decay modes of the new scalar



Decay Mode	$\phi \to \gamma\gamma$	$\phi \to \gamma f f (jj)$	$\phi \to \gamma WW$	Total
Width (GeV)	5.0	1.9 (0.86)	0.79	7.6
BR (%)	65	25 (11)	10	-

BR is independent of Λ, only depends on M_ϕ (here 1 TeV)

Production of the new scalar



Central exclusive production

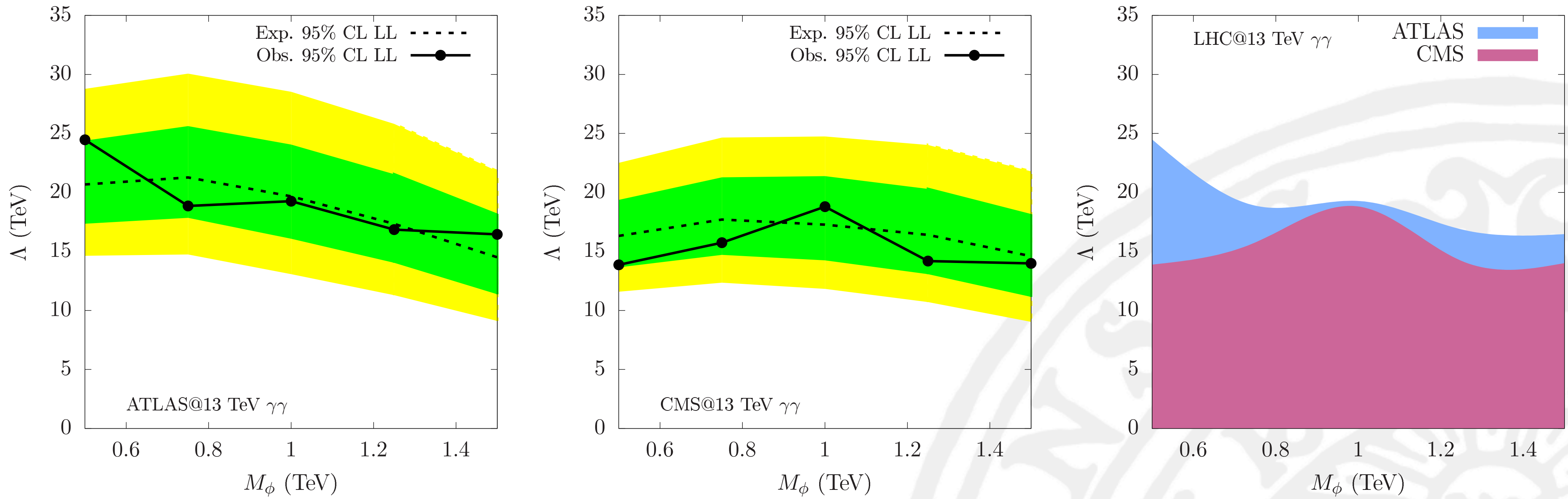
VBF-like

Associated prod with γ

Production mode	$\gamma\gamma \to \phi$	$\gamma p \to \phi j$	$pp \to \phi jj$	$pp \to \phi\gamma$	$pp \to \phi\gamma j$	$pp \to \phi\gamma jj$
CS@8TeV (fb)	32.18	7.841	0.451	0.182	0.095	0.043
CS@13TeV (fb)	110.5	29.94	1.846	1.116	0.711	0.396

Different from most proposals for the 750 GeV "excess" in that it is produced in γγ or qq initial states

Exclusion limits on M_ϕ and Λ



We have recast the limits from LHC for our production processes using our implementation of the model in MadGraph → lower limits on Λ of about 18 TeV

Plots from arXiv:1601.00624
Data from ATLAS-CONF-2016-059 and arXiv:1609.02507 (CMS)

Generalization to SU(3) × SU(2) × U(1)

But it is actually inconsistent to only let $\alpha_{EM} = e^2/4\pi$ be set by a scalar:

The SM of course mixes the $SU(2)_L$ coupling g and the $U(1)_Y$ coupling g′ into e, so to be consistent:

$$g(x) = g_0 \varepsilon_2(x)$$
$$g'(x) = g'_0 \varepsilon_1(x)$$

where $\varepsilon_1(x)$ and $\varepsilon_2(x)$ are scalar fields

This means θ_W is dynamical as well as M_W and M_Z!

Also add $g_3(x) = g_3^0 \varepsilon_3(x)$

making α_{EM} and α_S dynamical with associated scalar

Generalization to SU(2) × U(1)

Let us write:

$$g(x) = g_0 \varepsilon_2(x) \qquad \varepsilon_2 = e^{S/\Lambda} \simeq 1 + S/\Lambda$$

where

$$g'(x) = g'_0 \varepsilon_1(x) \qquad \varepsilon_1 = e^{S'/\Lambda'} \simeq 1 + S'/\Lambda'$$

Then for the SU(2) gauge field W and U(1) gauge field B:

(D. Kimberley and J. Magueijo, hep-ph/0310030)

$$\mathcal{L} = \frac{1}{2\Lambda} S W_{\mu\nu} W^{\mu\nu} + \frac{1}{2\Lambda'} S' B_{\mu\nu} B^{\mu\nu}$$

Thus the gauge boson masses and mixing will vary.

$$\tan\theta_w = \frac{g_0}{g'_0} e^{(S/\Lambda - S'/\Lambda')}$$

Note: $G_F = \sqrt{2}\, g^2/8M_W^2$ does not vary!

Generalization to SU(2) × U(1)

Switch to physical fields: $$B_\mu = c_w A_\mu - s_w Z_\mu$$
$$W^3_\mu = s_w A_\mu + c_w Z_\mu$$

So that

$$\mathcal{L} = \frac{1}{2}\left(\frac{s_w^2}{\Lambda}S + \frac{c_w^2}{\Lambda'}S'\right)F_{\mu\nu}F^{\mu\nu} + \frac{1}{2}\left(\frac{c_w^2}{\Lambda}S + \frac{s_w^2}{\Lambda'}S'\right)Z_{\mu\nu}Z^{\mu\nu}$$
$$+ s_w c_w\left(\frac{S}{\Lambda} - \frac{S'}{\Lambda'}\right)F_{\mu\nu}Z^{\mu\nu} + \frac{1}{2\Lambda}SW^+_{\mu\nu}W^{-\mu\nu}$$

Finally, S and S′ are not mass eigenstates, so we define

$$\begin{pmatrix}\phi \\ \phi'\end{pmatrix} = \begin{pmatrix}\cos\alpha & \sin\alpha \\ -\sin\alpha & \cos\alpha\end{pmatrix}\begin{pmatrix}S \\ S'\end{pmatrix}$$

where the mixing is determined from the scalar potential

Scalar potential

If we have n new scalars, the potential is in general

$$V = \sum_{i,j} \mu_{ij}^2 \phi_i \phi_j + \sum_{i,j,k} A_{ijk} \phi_i \phi_j \phi_k + \sum_{i,j,k,l} \lambda_{ijkl} \phi_i \phi_j \phi_k \phi_l$$

$$+ \sum_i \alpha_i \phi_i |\Phi|^2 + \sum_{ij} \beta_{ij} \phi_i \phi_j |\Phi|^2 + \mu^2 |\Phi|^2 + \lambda |\Phi|^4$$

The coeffients are all symmetric in the indices

→ 3 scalars: 42 parameters

→ 9 scalars: 761 parameters

→ n scalars: $n + 2 + 2\binom{n+1}{2} + \binom{n+2}{3} + \binom{n+3}{4}$

All gauge groups

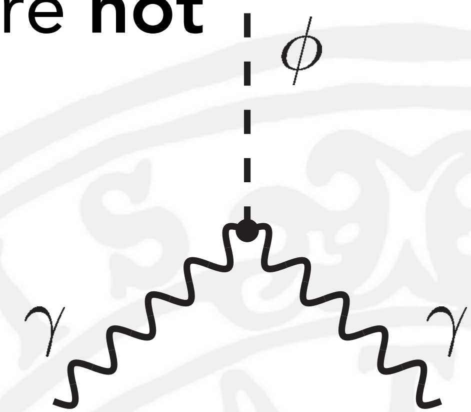
- The SU(3) scalar will similarly couple to gluons
- For SU(2) and U(1) there is mixing due to the Weinberg angle and from the scalar potential
- For SU(3): only mixing from scalar potential
- Possible signature of SU(3) scalar: scalar resonance in dijets at LHC

- The mixing parameters should be determined from a scalar potential, but we take the approach that the mixings are our phenomenological parameters

Note about the new scalars

The new scalars are real, neutral fields and are **not** charged under the gauge groups

They interact with gauge bosons as ϕF^2 = (non-renormalizable interactions)



E.g. the g_3-scalar ϕ_3 does not carry color, but it interacts directly with gluons

Generalize to Yukawa sector

Here, there's previous work on similar ideas:
flavons; mass varying neutrinos in cosmology

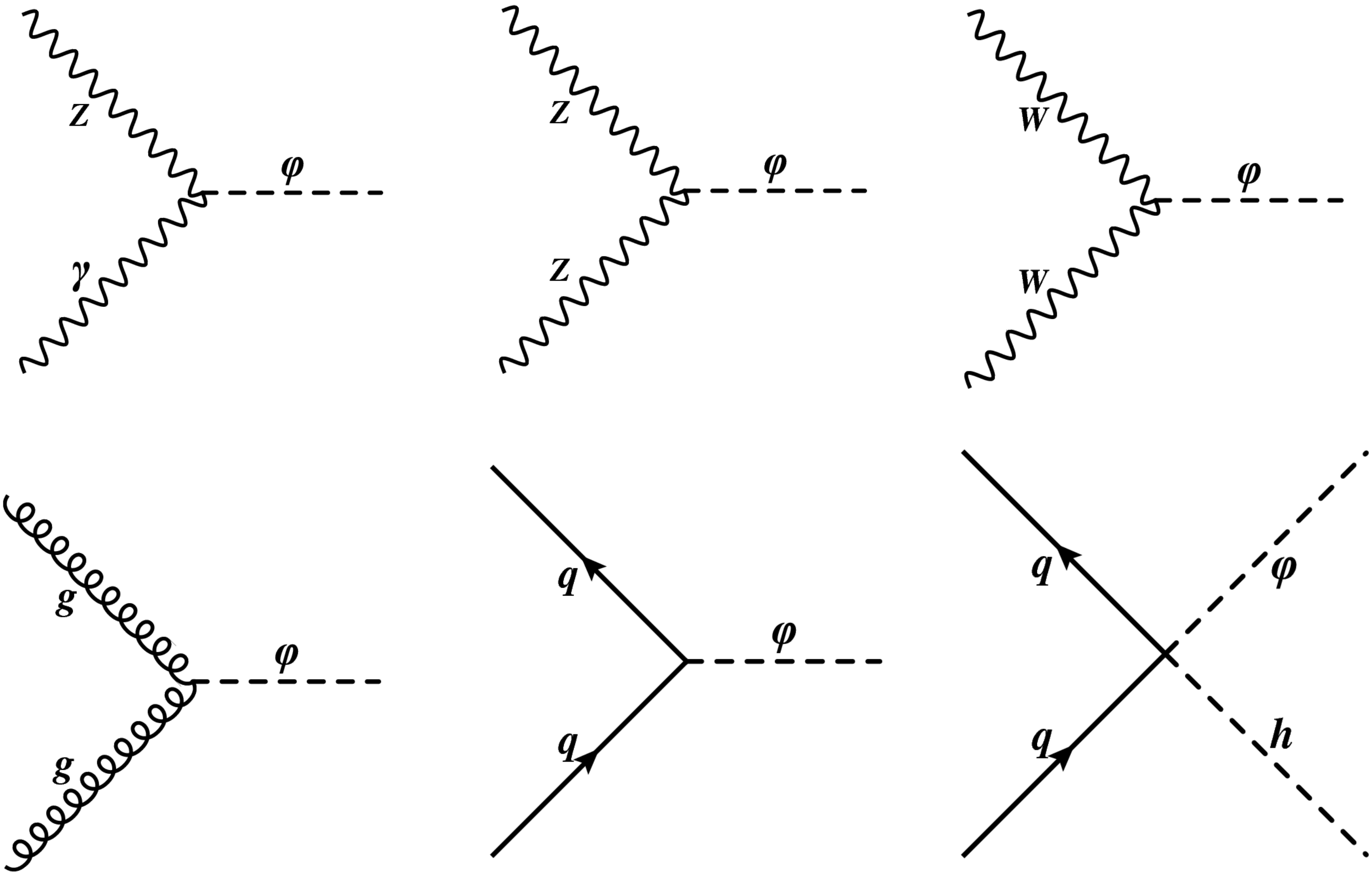
Here we introduce one new scalar for each Yukawa coupling → 9 new scalars (to start with for diagonal L_f)

Yukawa Lagrangian: $$\mathcal{L}_f = -\frac{y_f v}{\sqrt{2}}\left(1+\frac{h}{v}\right)\bar{\psi}_f\psi_f$$

Dynamical Yukawa: $$y_f(x) = y_{f,0}\left(1+\frac{\phi(x)}{\Lambda}\right)$$

Gives interactions: $$\mathcal{L}_{\text{int}} \supset \frac{y_f v}{\sqrt{2}\Lambda}\left(\phi+\frac{\phi h}{v}\right)\bar{\psi}_f\psi_f$$

Some types of new vertices (here φ is a general scalar)



Phenomenology

- There will be many new scalars
- They can in principle all mix, but the mixings are free parameters
- Can produce scalars in gg, γγ, VBF, associated with tt
- Decays into gg, γγ, γZ, ZZ, WW, ffh
- If mixings are small: not all of these possibilities
- If large mixings: can look similar to a heavy higgs
- Flavor violation in Yukawa sector?

- Work in progress…

Summary & outlook

- Dynamical couplings given by fields with no free parameters is a natural idea in UV completions
- Leads to the existence of many new real scalar fields that mix with each other and the Higgs(es)

  → Interesting phenomenology
- How light can they be?
- Cosmology? Astrophysics? Flavor physics?