Dark Energy at Colliders?

Philippe Brax, IPhT Saclay

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Outline

1-Dark Energy and New Scales in Physics

a) Dark Energy

b) Dark Energy Couplings

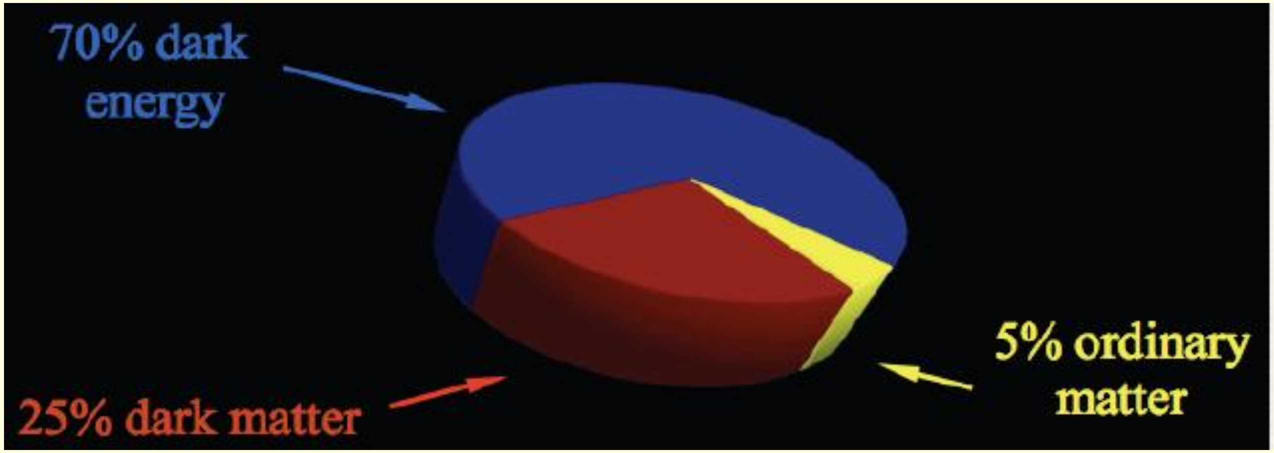
2-Collider Tests of Dark Energy

a) Z-width

b) Electro-weak Precision Tests

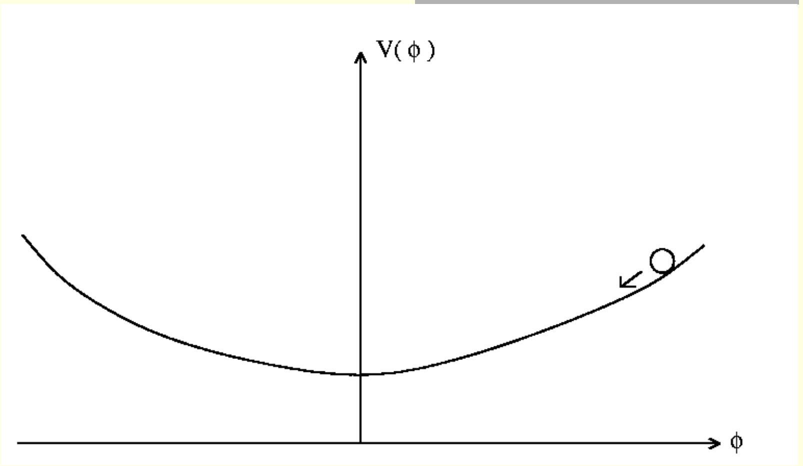
c) Higgs Production

The Big Puzzle

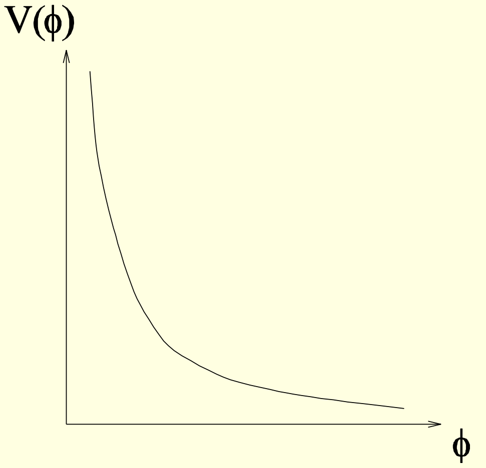


Dark Energy?

Like during primordial inflation, scalar fields can trigger the late acceleration of the universe.

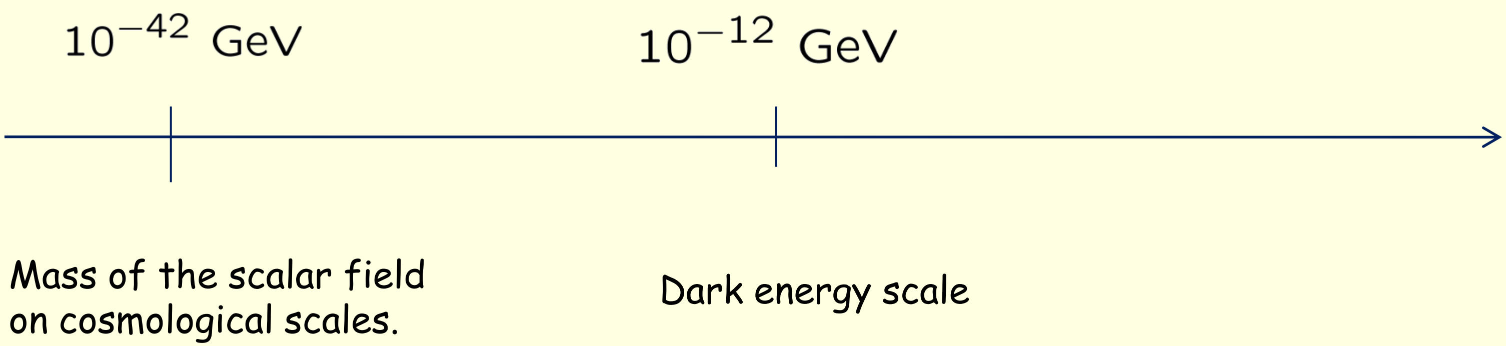


An attractive possibility: runaway behaviour.



The mass of the field now is of order of the Hubble rate. Almost massless.

New Scales in Physics



The dark energy scale is tantalizingly close to the neutrino mass scale and the scale at which gravity has been tested…

Do Scalars Couple to Matter?

Effective field theories with gravity and scalars

$$S=\int d^4x\sqrt{-g}\left(\frac{1}{16\pi G_N}R-\frac{1}{2}(\partial\phi)^2-V(\phi)+\mathcal{L}_m(\psi_m, A^2(\phi)g_{\mu\nu})\right)$$

Motivated by extra-dimensions, f(R) models…

Coupling of scalar to matter:

$$\alpha=\frac{\partial \ln A}{\partial\phi}$$

Gravitational Tests

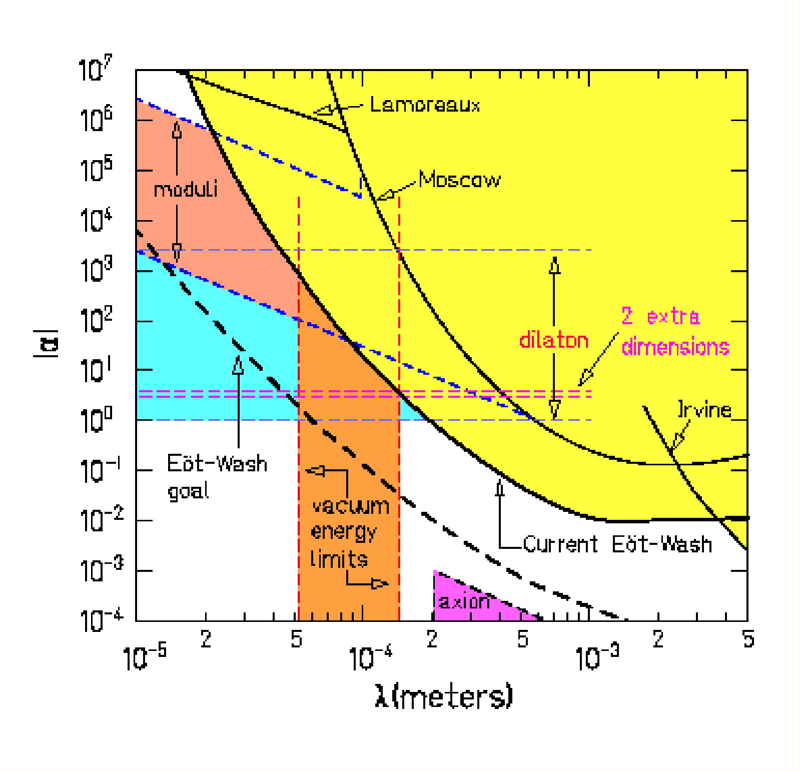
Non-existent fifth force if the scalar field has a mass greater than

$$m \geq 10^{-3} \text{ eV}$$

If not, strong bound from Cassini experiments on the gravitational coupling:

$$\alpha \leq 10^{-2}$$

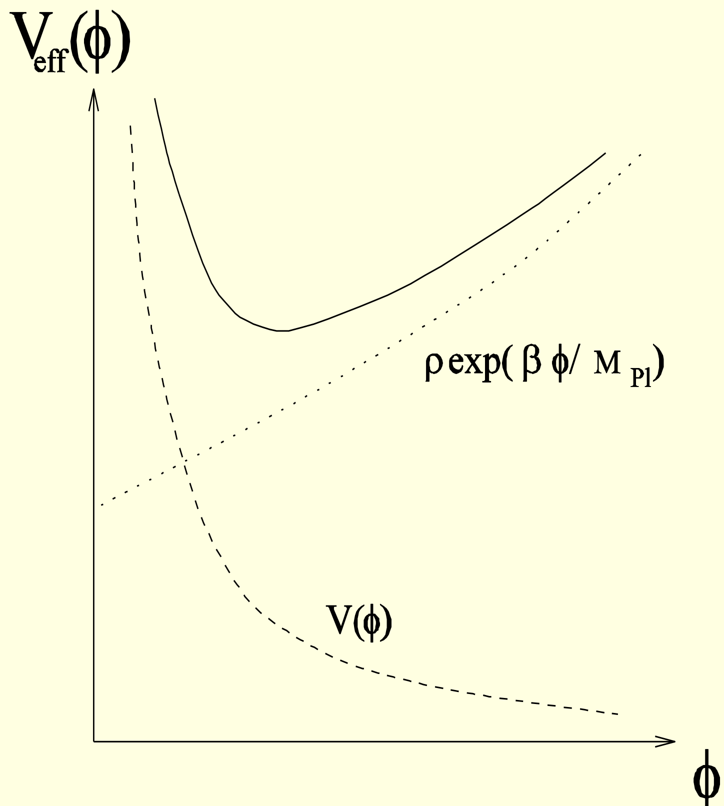
If coupling O(1) need new mechanism



The Chameleon Mechanism

When coupled to matter, scalar fields have a matter dependent effective potential:

$$V_{eff}(\phi) = V(\phi) + \rho_m A(\phi)$$



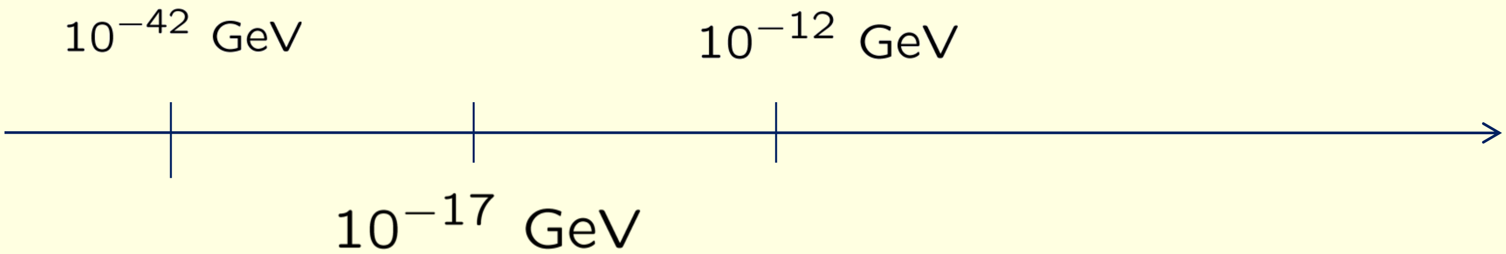
Chameleon field: field with a matter dependent mass

A way to reconcile gravity tests and cosmology:

Nearly massless field on cosmological scales

Massive field in the laboratory

New Scales in Physics



Typical scale of chameleon
mass in in collider vacuum.

Gauge Coupling

$$L_{\mathrm{eff}} = \frac{e^2\alpha}{3(4\pi)^2 m_{\mathrm{Pl}}}\phi F_{ab}F^{ab}$$

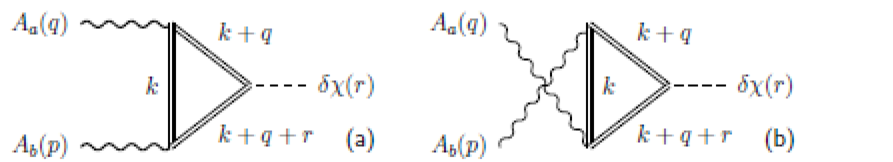


Figure 1. Diagrams contributing to the leading interaction between dark energy and the electroweak gauge bosons, which determine an effective operator acting on $A_a(q)A_b(p)\chi(r)$. Note that the momentum carried by χ is taken to flow into the diagram. Double lines represent a species of heavy fermion charged under $\mathrm{SU(2)}\times\mathrm{U(1)}$.

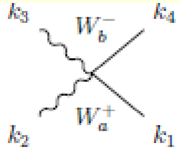
When the coupling to matter is universal, and heavy fermions are integrated out, a gauge coupling is induced. Other contribution from conformal anomaly too.

Effective Action and Couplings

The coupling involves two unknown coupling functions (gauge invariance):

$$
\begin{aligned}
S &= -\frac{1}{4}\int d^4x\Big\{2B(\beta\chi)(\partial^a W^{+b} - \partial^b W^{+a})(\partial_a W^-_b - \partial_b W^-_a) + 4m_W^2 B_H(\beta_H\chi)W^{+a}W^-_a \\
&+ B(\beta\chi)(\partial^a Z^b - \partial^b Z^a)(\partial_a Z_b - \partial_b Z_a) + 2m_Z^2 B_H(\beta_H\chi)Z^a Z_a \\
&+ B(\beta\chi)(\partial^a A^b - \partial^b A^a)(\partial_a A_b - \partial_b A_a)\Big\},
\end{aligned}
$$

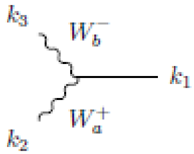
At one loop the relevant vertices are:



$$\longmapsto \frac{\bar{B}''\beta^2}{2}\left[\eta^{ab}(k_2\cdot k_3 - \epsilon m_W^2) - k_2^b k_3^a\right],$$

$$\epsilon = \frac{\bar{B}''_H}{\bar{B}''}\frac{\beta_H^2}{\beta^2}$$

$$\beta = \frac{1}{M}$$

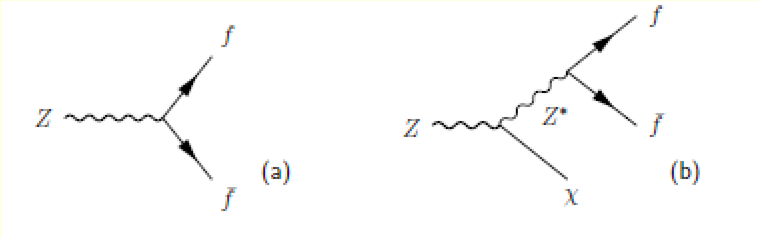


$$\longmapsto \bar{B}'\beta\left[\eta^{ab}(k_2\cdot k_3 - \gamma m_W^2) - k_2^b k_3^a\right],$$

$$\gamma = \frac{\bar{B}'_H}{\bar{B}'}\frac{\beta_H}{\beta}$$

Z-Width

Dark energy scalars being very light and coupling to the Z boson may lead to an increase of the Z width (similar to neutrinos).



$$\frac{\Gamma(Z \to \chi f \bar{f})}{\Gamma(Z -> f \bar{f})} \approx \frac{1}{80\pi^3} \frac{M_Z^2}{M^2}$$

This leads to a weak bound on M greater than 60 GeV. Stronger bounds follow from precision tests.

Higgs Screening

- As Higgs mass taken to infinity, should recover divergences of SM without Higgs: quadratic divergences of self-energy. Higgs mass acts as a loose cut-off so in principle:

$$\rho \equiv \frac{M_W^2}{M_Z^2 \cos^2\theta_W} = 1 + a_0 g^2 \frac{M_H^2}{M_Z^2} + a_1 g^2 \ln \frac{M_H^2}{M_W^2} + \ldots \equiv 1 + \alpha T$$

- Unfortunately it turns out that $a_0 = 0$

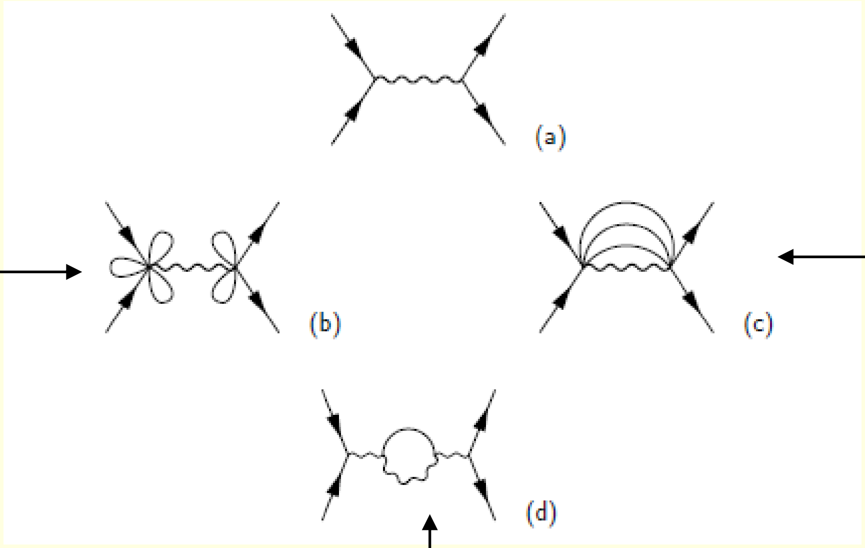
- Dark energy scalar like Higgs scalar: highly sensitive to high energy physics (UV completion):

$$g^2 \to \frac{M_Z^2}{M^2}, \quad M_H \to M$$

-
- Large corrections O(1)??

Vacuum Polarisation

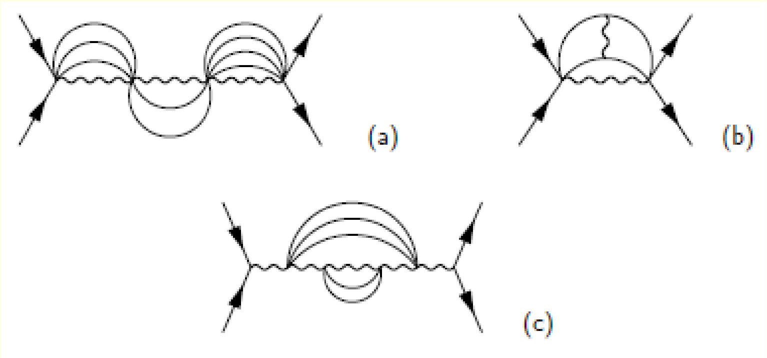
Daisies



Bridges

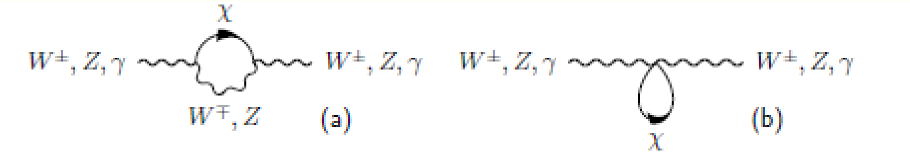
Oblique Corrections

Rainbows, Daisies and Bridges



Higher order corrections all suppressed. One loop contributions all momentum independent at leading order in q^2/M^2

Self-Energy Corrections I



The corrected propagator becomes:

$$\Delta(k^2) = \frac{1}{k^2 + M_A^2 - \Pi_{AA}^{(0)}(k^2)}$$

Measurements at low energy and the Z and W poles imply ten independent quantities. Three have to be fixed experimentally. One is not detectable hence six electroweak parameters: STUVWX

$$\Pi'_{\gamma\gamma}(q^2),\ \Pi'_{Z\gamma}(q^2), \Pi_{ZZ}(q^2),\ q^2 = 0, -M_Z^2$$

$$\Pi'_{ZZ}(-M_Z^2), \Pi'_{WW}(-M_W^2), \Pi_{WW}(0), \Pi_{WW}(-M_W^2)$$

Self-Energy Corrections II

The self energy can be easily calculated:

$$\begin{aligned}\Pi_{AA}(k^2) &= \frac{\beta^2}{8\pi^2}\frac{\bar{B}'^2}{\bar{B}}\int_0^1 dx\,\Big\{\frac{2k^2+\gamma^2 M_A^2}{4}\left[\Lambda^2+\frac{\Lambda^2}{2}\frac{\Lambda^2}{\Lambda^2+\Sigma^2}-\Sigma^2\ln\left(1+\frac{\Lambda^2}{\Sigma^2}\right)\right]\\ &+(xk^2+\gamma M_A^2)^2\left[-\frac{1}{2}\frac{\Lambda^2}{\Lambda^2+\Sigma^2}+\frac{1}{2}\ln\left(1+\frac{\Lambda^2}{\Sigma^2}\right)\right]\\ &-\frac{\Omega}{2}(k^2+\epsilon M_A^2)\left[\frac{\Lambda^2}{2}-\frac{M_X^2}{2}\ln\left(1+\frac{\Lambda^2}{M_X^2}\right)\right]\Big\}\end{aligned}$$

$$\Omega = \frac{B''B}{B'^2}$$

The self energy parameters all involve quadratic divergences:

$$\Pi_{AA}(k^2) = \frac{g^2}{M^2}[M_A^2\alpha_{0,A}+\alpha_{2,A}k^2+\alpha_{4,A}k^4+O(\frac{k^2}{M_W^2})]$$

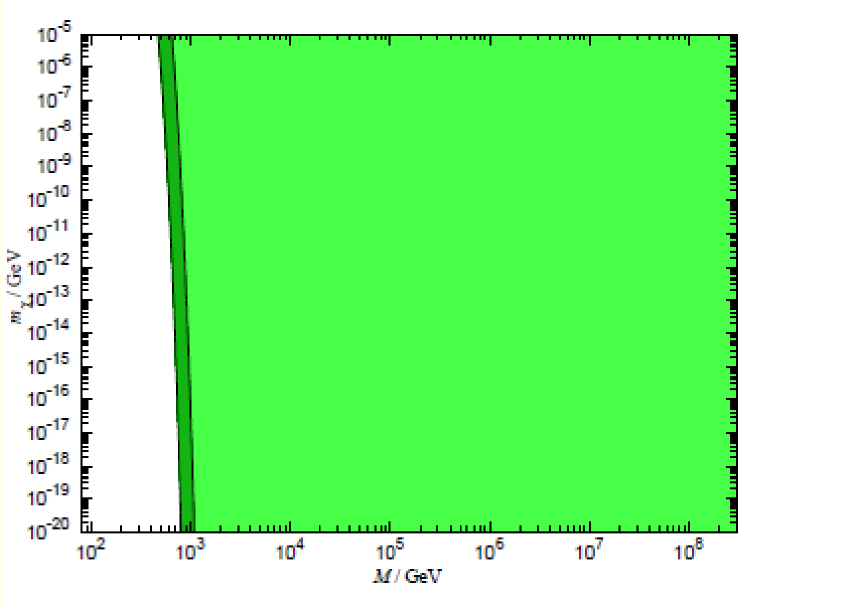
For instance: $\alpha_0 = \frac{\Lambda^2}{4}(\frac{\gamma^2}{2}-\Omega\epsilon)+16(6\ln\frac{\Lambda^2}{M_A^2}-1)\gamma^2 M_A^2+\dots$

The quadratic divergences cancel in all the precision tests:

$$\alpha T = \frac{g^2}{M^2}(\alpha_{0,Z}-\alpha_{0,W})$$

Experimental Constraints

mass



Inverse Coupling

Dark Energy Screening

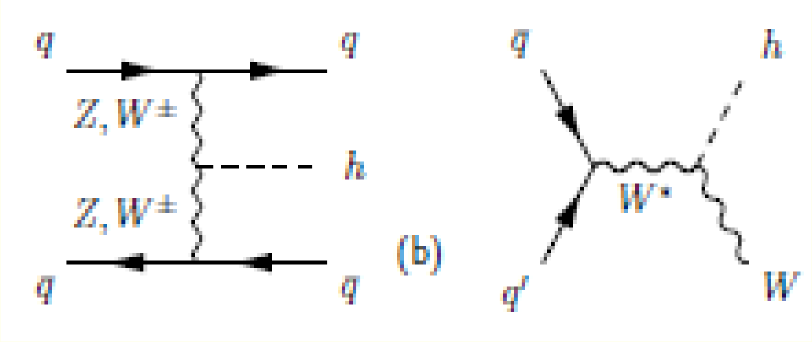
Vacuum Polarisation sensitive to the UV region of phase space where the difference between the W and Z masses is negligible

Gauge invariance implies the existence of only two coupling functions with no difference between the W and Z bosons in the massless limit (compared to the UV region)

No difference between the different particle vacuum polarisations, hence no effects on the precision tests.

Higgs Production

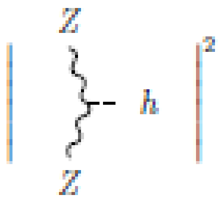
The dark energy scalar can also couple to the Higgs. This will influence the W fusion and W-Higgstrahlung production rates.



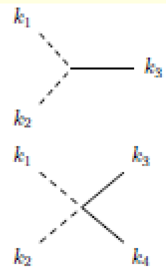
Higgs-Scalar Coupling

$$S = -\frac{1}{2}\int d^4x[B_H(\beta_H\chi)|DH|^2 - C_H(\beta_H\chi)\mu^2|H|^2 + \ldots]$$

The dark energy scalar field influences the Higgs wave function renormalisation. Other effects in to the gauge sector are suppressed as we have already seen.



$$\propto M_Z^4 G_F \times \text{wavefunction renormalizations},$$

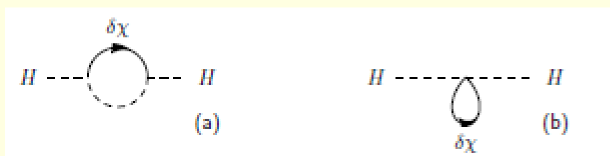


$$\rightarrow \frac{\beta_H}{2}\left\{B'_H(k_2 \cdot k_3) - C'_H M_H^2\right\},$$

$$\rightarrow \frac{\beta_H^2}{4}\left\{B''_H(k_2 \cdot k_3) - C''_H M_H^2\right\},$$

Higgs-scalar Feynman rules

$\Pi_{HH}(k^2)$



Higgs self-energy

$\downarrow$

Wave function renormalisation

The new oblique parameter is:

$$\alpha R = \frac{d}{dk^2}\Pi_{HH}(k^2)|_{k^2=-M_H^2} + \frac{\Pi_{ZZ}(0)}{M_Z^2}$$

The Higgs production rate is then modified:

$$\frac{\Gamma(WW \to h)}{\tilde{\Gamma}(WW \to h)} = 1 + \alpha R$$

As expected, the dark energy correction is quadratically divergent depending on the cut-off of the theory. Hence, one might expect large deviations from the SM due to the presence of very light dark energy scalars.

$$\alpha R = \frac{\beta_H^2 \Lambda^2}{32\pi^2}\frac{B'^2_H}{B}[\frac{1}{2}(1+\frac{B}{B_H}) - 2\frac{B''_H B}{B'^2_H}] = \mathcal{O}(1)$$

Conclusions

- When considering dark energy as resulting from an effective field theory, its coupling to matter as seen in the precision tests of the electro-weak physics is screened. This is due to the UV sensitivity of the vacuum polarisation and gauge invariance.
- Possibility of large effects in the Higgs sector due to the mixing with the dark energy scalar.