Hidden Photons

I. Physics beyond the SM from the bottom up

I.1 Why we need new physics

Theoretical/aesthetic shortcomings of the SM:

- $\mathcal{O}(30)$ free parameters
- Huge hierarchy of relevant scales:

$$\left.\begin{aligned} &\text{EW:} \quad m_W \sim m_Z \sim 100\,\text{GeV} \\ &\text{Gravity:} \quad M_{Pl} \sim 10^{19}\,\text{GeV} \end{aligned}\right\} \quad \left(\frac{m_W}{M_{Pl}}\right)^2 \sim 10^{-17.2}$$

- Gravity is not on the same footing as other interactions
- Break down of SM at finite energies

Essential shortcomings:

- Energy budget of the universe
  - ▸ 70% dark energy: component with negative pressure ?
  - ▸ 25% dark matter: component that interacts gravitationally, but is not composed of ordinary e^-, p^+, n (cf. CMB) ?
  - ▸ 5% baryons: what is the origin of matter-antimatter asymmetry ?

$\Rightarrow$ >95% of the energy budget of the universe unexplained by SM!

I.2 (Possible) observational evidence for new physics

- Positron excess in cosmic rays measured at earth with Pamela/FermiLAT/AMS-02
- Excess γ rays at $\sim$GeV energies from galactic centre
- DAMA/Libra annual modulation excess events.
- $(g-2)_\mu$ deviation from SM prediction by $\sim 4\sigma$
- Flavor anomalies $R_{D^{(*)}}, R_{K^{(*)}}$

$$R_{D^{(*)}} = \frac{Br(B \to D^{(*)} \tau \nu)}{Br(B \to D^{(*)} \mu \nu)}, \quad R_{K^{(*)}} = \frac{Br(B \to K^{(*)} \mu^+ \mu^-)}{Br(B \to K^{(*)} e^+ e^-)}$$

I.3 Towards constructing a QFT for new physics

- The fundamental building blocks of a QFT are the n-point correlation functions $\langle 0|T\,\varphi(x_1)\,\varphi(x_2)\ldots|0\rangle$. Assuming canonical quantisation works we obtain these from the path integral:

$$\langle 0|T\,\varphi(x_1)\,\varphi(x_2)\ldots|0\rangle \sim \frac{1}{i}\frac{\delta}{\delta J(x_1)}\,\frac{1}{i}\frac{\delta}{\delta J(x_2)}\cdots\int \mathcal{D}\varphi\, e^{i\int d^4x\,[\mathcal{L}[\varphi]+J\varphi]}\Big|_{J=0}$$

The fundamental quantity is thus the (dimensionless) action:

$$S[\varphi] = \int d^4x\,\mathcal{L}[\varphi]$$

with mass dimension $[S] = 0 = \underbrace{[\int d^4x]}_{-4} + \underbrace{[\mathcal{L}]}_{4}$

- So we find that the Lagrangian density $\mathcal{L}$ has mass dimension dim $=4$ and so must have every term that we include in $\mathcal{L}$. This motivates new physics operators with dim $=4$ and indeed we find that <u>operators with dim ≤ 4 are special</u>:

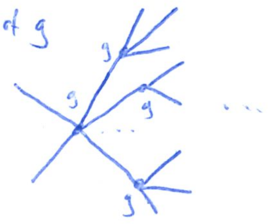
<u>i) (Perturbative) renormalizable:</u>

- A theory with any $[g_n] < 0$ is nonrenormalizable. To see this consider:

$\mathcal{L}_{int} \supset g\,\varphi^m$

$$\Rightarrow \quad \sigma \sim g^n\, E^{\overbrace{-n\cdot[g]}^{\text{to compensate for scaling of } g}-2}$$

$(\text{as } [\sigma \sim E^{-2}] = -2)$



$[\mathcal{L}_{int}] = 4 = [g] + m[\varphi]$

If $m[\varphi] \leq 4$

$\Rightarrow [g] \geq 0$ ✓

If $[g] < 0$ we always find n such that $-n[g] - 2 > 0$

↳ Perturbativity breaks down and cross section explodes at high energies

ii) Operators with dim ≤ 4 are most relevant at low energies. Therefore, they lead to observable consequences in the universe today and can be tested by (low energy) experiments

iii) Operators with dim ≤ 4 of low-energy effective theory that are generated at high scale M are unsuppressed by M

$$\Delta g \sim M^{[g]}$$

$$(\text{if } [g]=0 \Rightarrow \Delta g \sim \log(M))$$

I.4 Portals to the Hidden Sector

Previous discussion of operators with dim ≤ 4 motivates BSM model building with dim ≤ 4 operators.

Strategy
- Replace SM fields (or combinations) that are singlet under SM gauge group by hidden sector fields
- Replace SM couplings with $[g] > 0$ by hidden sector fields

a) Neutrino Portal

- The combination $\bar{L}_L \tilde{H}$ is a singlet under the SM gauge group.

$(\tilde{H} = i\tau_2 H^*)$ (but not under the Poincaré group $\rightarrow$ spin $\frac{1}{2}$)

$\Rightarrow$ We can add a right-handed fermion ψ_R:

$$\mathcal{L}_{\text{neutrino portal}} = -Y_{\text{neut}} \bar{L}_L \tilde{H} \psi_R$$

- can add any number of ψ_R's $\Rightarrow Y_{\text{neut}}$ is a $3\times n$ Yukawa matrix
- this generates neutrino masses for $\langle \tilde{H} \rangle \neq 0$

b) Higgs portal

- The combination $H^\dagger H$ is a SM singlet.

$\Rightarrow$ We can add a hidden sector singlet or multiplet:

$$\mathcal{L}_{\text{singlet Higgs portal}} = -(\eta_S S + \lambda_S S^2) H^\dagger H$$

$$\mathcal{L}_{\text{non-singlet portal}} = -\lambda_p \Phi^\dagger \Phi H^\dagger H$$

- If the hidden sector scalar obtains a VEV $\langle\Phi\rangle \neq 0$ the SM higgs will mix with Φ:

$$\Phi = \frac{\Phi_0}{\sqrt{2}} + \frac{\varphi}{\sqrt{2}} \quad ; \quad H = \frac{v}{\sqrt{2}} + \frac{h}{\sqrt{2}}$$

$$\left.\begin{array}{l} |H|^4 \sim v^2 h^2 \\ |H|^2|\Phi|^2 \sim v\Phi_0\, h\varphi \\ |\Phi|^4 \sim \Phi_0^2\, \varphi^2 \end{array}\right\} \Rightarrow \text{non-diagonal mass term } (h, \varphi)\begin{pmatrix} v^2 & v\Phi_0 \\ v\Phi_0 & \Phi_0^2 \end{pmatrix}\begin{pmatrix} h \\ \varphi \end{pmatrix}$$

$\Rightarrow$ Upon diagonalization of the mass term the fields h and φ will mix into the mass eigenstates

c) Vector portal

- For Abelian gauge symmetries the field strength by itself is a SM singlet. This can be seen explicitly from the gauge transformation:

$$V_\mu \to V_\mu + \partial_\mu \chi$$

$$\Rightarrow V_{\mu\nu} = \partial_\mu V_\nu - \partial_\nu V_\mu \to \partial_\mu (V_\nu + \partial_\nu \chi) - \partial_\nu (V_\mu + \partial_\mu \chi) = V_{\mu\nu}$$

- With $[V_{\mu\nu}] = 2$ we can construct the dim $=4$ vector portal of a new gauge boson with the SM hypercharge:

$$\mathcal{L}_{\text{kinetic mixing}} = -\frac{\epsilon_Y}{2} B_{\mu\nu} V^{\mu\nu}$$

Note $[\epsilon_Y] = 0$

This will effectively mix the new boson V with the hypercharge boson B: