II. The Hidden Photon

- The gauge boson V_μ associated with a new "dark" $U(1)_d$ symmetry provides a portal to the dark sector for the SM. The minimal Lagrangian allowed by gauge symmetry and renormalizability is given by:

$$\mathcal{L}_d = -\frac{1}{4} V_{\mu\nu} V^{\mu\nu} - \frac{\epsilon_Y}{2} B_{\mu\nu} V^{\mu\nu} + \frac{m_V^2}{2} V_\mu V^\mu - g_d j_d^\mu V_\mu$$

with the dark current of fields charged under $U(1)_d$:

$$j_d^\mu = Q_d^\psi \bar{\psi} \gamma^\mu \psi$$

II. 1 Origin and magnitude of kinetic mixing

- In a full UV complete theory (in particular in GUTs with $G_{GUT} \to G_{SM} \times U(1)_d$) we will typically have fields ψ charged under both $U(1)_Y$ and $U(1)_d$. These will induce kinetic mixing via loop effects analogous to the self-energy contributions to propagators:

$\propto \epsilon_Y B_{\mu\nu} V^{\mu\nu}$

with

$$\epsilon_Y \approx -\underbrace{\frac{g_Y g_d}{16\pi^2}}_{10^{-2}\dots 10^{-4}} \sum_\psi Q_Y^\psi Q_d^\psi \underbrace{\log\left(\frac{M_\psi^2}{\mu^2}\right)}_{1\dots 10} \sim 10^{-2}\dots 10^{-4}$$

II.2 Gauge boson mass

- The new gauge boson V_μ can acquire mass in the same way that the weak bosons of the SM attain mass - via a Higgs mechanism. Suppose there is a new scalar Φ charged under $U(1)_d$ that acquires a VEV

$$\Phi = \frac{\phi_0}{\sqrt{2}} + \frac{\varphi}{\sqrt{2}}$$

Then the kinetic term of the scalar becomes:

$$\mathcal{L}_\Phi = (D_\mu \Phi)^\dagger (D^\mu \Phi) \xrightarrow{VEV} (\partial_\mu + i g_d V_\mu) \frac{1}{\sqrt{2}}(\phi_0 + \varphi^*) (\partial^\mu - i g_d V^\mu) \frac{1}{\sqrt{2}}(\phi_0 + \varphi)$$

$$\supset \frac{g_d^2 \phi_0^2}{2} V_\mu V^\mu$$

Thus the mass reads $m_V = g_d \Phi_0$. If the symmetry breaking happens at or above the EW scale $\Phi_0 \gtrsim v$ and the theory is weakly coupled $g \sim \mathcal{O}(10^{-2})$ we will have typical masses of

$$m_V = g_d \Phi_0 \sim \mathcal{O}(\mathrm{GeV})$$

Side Remark 1

A very nice explanation and the original motivation for GeV-scale mediator masses is based on weak-scale SUSY breaking. In supersymmetric models the term

$$\mathcal{L} = -\frac{\epsilon_Y}{2} \int d^2\theta \, W_Y W_d$$

Contains a also a mixed D-term

$$V_{mix} = \epsilon D_Y D_d .$$

After EWSB the hypercharge D-term acquires a VEV through the MSSM two Higgs doublets:

$$\langle D_Y \rangle = \frac{g_Y}{2} \left(|H_u|^2 - |H_d|^2 \right) + \xi_Y$$

This leads to an effective Fayet-Illiopoulos term for $U(1)_d$

$$V_{FI,d} = \xi D_d \quad , \qquad \text{with } \xi = \epsilon_Y \left(-\frac{g_Y v^2 \cos 2\beta}{4} + \xi_Y \right)$$

With $\epsilon_Y \sim 10^{-3} .. 10^{-4}$ and $\langle D_Y \rangle \sim \mathcal{O}(v)$ one finds that $\xi \sim (1-5 \text{ GeV})^2$. One can then find a SUSY vaccum (with vanishing F- and D-terms) that breaks $U(1)_d$ when the scalar charged under $U(1)_d$ acquires a VEV at $\langle h' \rangle = \sqrt{\frac{2\xi}{g_d}}$. Then the boson mass reads

$$m_V^2 = g_d \xi \sim \mathrm{GeV} \quad (\text{for } g_d \text{ a weak coupling})$$

For details see e.g. [C. Cheung et al. 0902.3246].

Side Remark 2

The Lagrangian $\mathcal{L} = -\frac{1}{4} V_{\mu\nu} V^{\mu\nu} - \frac{m_V^2}{2} V_\mu V^\mu$ can be made gauge invariant by splitting off the longitudinal degree of freedom $V_\mu \to V_\mu + \frac{1}{m_V} \partial_\mu \Phi$.

Then the gauge transformations read

$$\delta V_\mu = \partial_\mu \lambda \quad , \quad \delta \Phi = -m_V \lambda$$

- This leads to the so-called Stückelberg Lagrangian

$$\mathcal{L}_{St} = -\frac{1}{4} V_{\mu\nu} V^{\mu\nu} - \frac{1}{2} (m_V V_\mu + \partial_\mu \Phi)(m_V V^\mu + \partial^\mu \Phi)$$

that is now manifestly gauge invariant. In principle, m_V is now a free parameter of the theory and can be chosen arbitrarily.

II.3 Why is it called "Hidden Photon"?

- In order to make contact with experiment we need to be able to calculate transition amplitudes and therefore be able to write down propagators of the mediator fields. Therefore, we have to get rid off the mixed $B_{\mu\nu} V^{\mu\nu}$ term by a non-unitary field redefinition that reads to leading order in ϵ_Y

$$\hat{B}_\mu = B_\mu - \epsilon_Y V_\mu \quad , \quad \hat{V}_\mu = V_\mu$$

However, EWSB will mix B and the neutral W boson. This will lead to an off-diagonal mass matrix for the three neutral (wide) bosons $\hat{B}$, $\hat{W}^3$ and $\hat{V}$

$$\mathcal{L}_{mass} = \frac{1}{2} (\hat{B}_\mu, \hat{W}^3_\mu, \hat{V}_\mu) \underbrace{\frac{v^2}{4} \begin{pmatrix} g_Y^2 & -g_Y g_2 & -g_Y^2 \epsilon_Y \\ -g_Y g_2 & g_2^2 & g_Y g_2 \epsilon_Y \\ -g_Y^2 \epsilon_Y & g_Y g_2 \epsilon_Y & \frac{4 m_V^2}{v^2}(1+\epsilon_Y^2) + g_Y^2 \epsilon_Y^2 \end{pmatrix}}_{M^2} \begin{pmatrix} \hat{B}^\mu \\ \hat{W}^{3\mu} \\ \hat{V}^\mu \end{pmatrix} + \mathcal{O}(\epsilon_Y^3)$$

- This mass matrix can be diagonalized by two consecutive rotations

$$R_1(\xi) R_2(\theta_W) = \begin{pmatrix} 1 & 0 & 0 \\ 0 & c_\xi & s_\xi \\ 0 & -s_\xi & c_\xi \end{pmatrix} \begin{pmatrix} c_W & s_W & 0 \\ -s_W & c_W & 0 \\ 0 & 0 & 1 \end{pmatrix}$$

- Finally, this will lead to the interaction term for the mass eigenstates, A, Z and A' taking into account $\epsilon_Y \ll 1$ and $m_V \ll m_Z$:

$$\mathcal{L}_{int} = \left(e\, j^\mu_{EM}, \frac{e}{s_W c_W} j^\mu_Z, g_d j^\mu_d\right) \begin{pmatrix} 1 & 0 & -\epsilon \\ 0 & 1 & 0 \\ 0 & \epsilon \tan\theta_W & 1 \end{pmatrix} \begin{pmatrix} A_\mu \\ Z_\mu \\ A'_\mu \end{pmatrix} + \mathcal{O}\left(\epsilon^2, \left(\frac{m_{A'}}{m_Z}\right)^2\right)$$

This means that the mass eigenstate A' couples to the EM current with a universal suppression factor $\epsilon = \epsilon_Y \cos\theta_W$:

$$\boxed{\mathcal{L}_{\text{int}\,A'} = -\epsilon e\, j^{\mu}_{EM} A'_{\mu}}$$

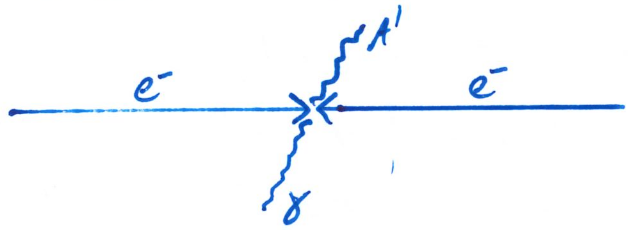
$\Rightarrow$ The A' couples to the SM in the same way as the photon A, but with strongly suppressed couplings – a hidden (massive) photon!

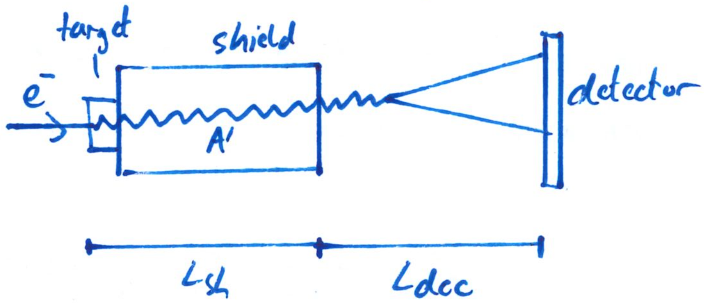
III. Hidden Photon searches

- Now that we know that Hidden Photons couple to the EM current we can ask ourselves how to best look for them. Two natural choices that involve a lot of EM interactions are an e^+e^--collider and an e^- beam dump.

III.1 Collider vs. beam dump

- We can estimate the collected luminosities per bunch of N_e electrons





$$\mathcal{L}^{coll} \simeq \frac{N_e^2}{A_b} \quad \text{— beam cross section}$$

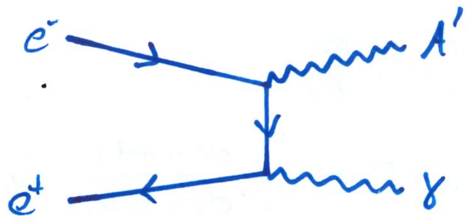
$$\mathcal{L}^{bd} \simeq N_e \frac{N_0\, \varrho_{sh} L_{sh}}{A} \quad (N_0\text{: Avogadro},\ A\text{: atomic weight})$$

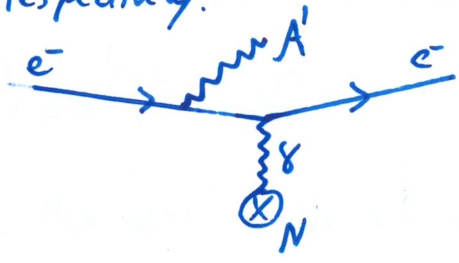
Therefore the beam dump luminosity per N_e electrons is larger by a factor of

$$\frac{\mathcal{L}^{bd}}{\mathcal{L}^{coll}} \simeq \frac{N_0\, \varrho_{sh} L_{sh} A_b}{A N_e} \simeq \frac{n_{sh}}{n_e} \times \frac{L_{sh}}{L_b} \simeq \mathcal{O}(10^6)$$

In a realistic setup a beam dump collects $\mathcal{O}(ab^{-1})$ of data per day and a collider per decade. This is a factor of $\sim \mathcal{O}(10^3)$.

- The A' production processes are associated production and bremsstrahlung for the collider and beam dump respectively.





The production cross sections roughly scale as

$$\sigma_{A'}^{coll} \sim \frac{\alpha^2 \epsilon^2}{E^2} \qquad\qquad \sigma_{A'}^{bd} \sim \frac{\alpha^3 Z^2 \epsilon^2}{m_{A'}^2}$$

For typical values of $\epsilon \simeq 10^{-4}$ and $m_{A'} = 50$ MeV (and an energy of $E \simeq 1$ GeV) the cross sections are roughly

$$\sigma_{A'}^{coll} \sim \mathcal{O}(fb) \qquad\qquad \sigma_{A'}^{bd} \sim \mathcal{O}(pb)$$

$\Rightarrow$ In summary, the high luminosity and the enhanced Hidden Photon production cross section make a beam dump experiment a prime candidate for Hidden Photon searches!

III.2 Hidden Photon searches at beam dump experiments

- The number of produced Hidden Photons in a beam dump, which decay in the fiducial volume of the detector is given by

$$N_{ev} = N_{A'}\, P_{dec} \cdot BR_{det} = N_e\, \sigma_{A'}\, n_{sh}\, L_{sh}\, P_{dec} \cdot BR_{det}$$

with N_e incident e^-, the A' production cross section, the decay probability P_{dec} and the A' branching fraction into detectable final states BR_{det}.

- In the Weizsäcker-Williams approximation the A' bremsstrahlungs production can be estimated to

$$\frac{d\sigma_{A'}}{d x_e} \simeq 4\alpha^3 \epsilon^2\, \xi(E_e, m_{A'}, Z, A) \sqrt{1-\frac{m_{A'}^2}{E_e^2}}\; \frac{1 - x_e + \frac{x_e^2}{3}}{m_{A'}^2 \frac{1-x_e}{x_e} + m_e^2 x_e} \propto \frac{\alpha^3 \epsilon^2 Z^2}{m_{A'}^2}$$

with the energy fraction $x_e = \frac{E_{A'}}{E_e}$ and the nucleus effective photon flux

$$\xi(E_e, m_{A'}, Z, A) = \int_{t_{min}}^{t_{max}} dt\, \frac{t - t_{min}}{t^2}\, G_2(t) \longleftarrow \text{electric form factor}$$

Hidden Photon decays

- The partial decay width of a Hidden Photon in a pair of charged leptons $\ell^+\ell^-$ can be obtained to be

$$\Gamma_{\ell^+\ell^-} = \frac{\alpha\epsilon^2}{3} m_{A'} \sqrt{1 - 4\frac{m_\ell^2}{m_{A'}^2}} \left(1 + 2\frac{m_\ell^2}{m_{A'}^2}\right)$$

As for the SM photon the hadronic decay width is given via $R(\sqrt{s}) = \frac{\sigma(e^+e^- \to had)}{\sigma(e^+e^- \to \mu^+\mu^-)}$ by

$$\Gamma_{had} = \Gamma_{\mu\mu} R(m_{A'})$$

so that full decay width reads $\Gamma_{A'} = \Gamma_{ee} + \Gamma_{\mu\mu}(1 + R(m_{A'})) + \Gamma_{\tau\tau}$.

By knowledge of the total decay width we can calculate the A' decay length in the lab

$$\ell_{A'} = \gamma\beta\tau_{A'} = \sqrt{\frac{1 + (\frac{p}{m_{A'}})^2}{1 + (\frac{m_{A'}}{p})^2}} \frac{1}{\Gamma_{A'}} \simeq \frac{E_{A'}}{m_{A'}} \frac{1}{\Gamma_{A'}} \propto \frac{3 E_{A'}}{\alpha\epsilon^2 m_{A'}^2}$$

$$\simeq 8\,\text{cm} \frac{E_{A'}}{1\,\text{GeV}} \left(\frac{10^{-4}}{\epsilon}\right)^2 \left(\frac{10\,\text{MeV}}{m_{A'}}\right)^2$$

- This leads us to the probability that the A' decays behind the shield L_{sh} but before leaving the detector at $L_{sh} + L_{dec}$:

$$P_{dec} = e^{-\frac{L_{sh}}{\ell_{A'}}} \left(1 - e^{-\frac{L_{dec}}{\ell_{A'}}}\right)$$

Beam Dump sensitivity

- We can derive limits on the Hidden Photon parameter space by comparing the 95% C.L. limit on the number of signal events N^{95} above background to the expected number of A' decay events

$$N_{ev} \simeq N_e \frac{N_0 X_0}{A} \int_{m_{A'}}^{E_0 - m_e} dE_{A'} \int_{E_{A'}+m_e}^{E_0} dE_e \int_0^{T_{sh}} dt_{sh} \left[I_e(E_0, E_e, t_{sh}) \frac{1}{E_e} \frac{d\sigma}{dx_e}\bigg|_{x_e = \frac{E_{A'}}{E_e}} e^{-\frac{L_{sh}}{\ell_{A'}}} \left(1 - e^{-\frac{L_{dec}}{\ell_{A'}}}\right) \right] \times BR_{det}$$

where $I_e(E_0, E_e, t_{sh})$ is the distribution of the electron energy E_e after passing through t_{sh} radiation lengths of material before radiating the A'. Here, A is the atomic weight of the shield material and X_0 its unit radiation length, N_0 denotes Avogadro's number.