Shining Light on Dark Matter,
One Photon at a Time

by

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Abstract

A search is conducted for new physics in final states containing a photon and missing transverse momentum in proton-proton collisions at $\sqrt{s} = 13$ TeV. The data collected by the CMS experiment at the CERN LHC correspond to an integrated luminosity of 35.9 inverse femtobarns. No deviations from the predictions of the standard model are observed. The results are interpreted in the context of dark matter production and limits on new physics parameters are calculated at 95% confidence level. For the two simplified dark matter production models considered, the observed (expected) lower limits on the mediator masses are both $950\,(1150)$ GeV for 1 GeV dark matter mass.

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Acknowledgments

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Chapter 1

Motivation

1.1 The Standard Model

The Standard Model (SM) of particle physics describes the physical properties and dynamics of fermions, the fundamental constituents of matter, and their interactions in the language of a Lorentz-invariant quantum field theory (QFT). The Standard Model consists of a set of fermion fields, shown in Table 1.1 and the local gauge symmetry group that acts on them

$$G_{\mathrm{SM}} = \mathrm{SU}(3)_C \times \mathrm{SU}(2)_L \times \mathrm{U}(1)_Y, \tag{1.1}$$

which is composed of the subgroups

$$G_{\mathrm{QCD}} = \mathrm{SU}(3)_C \qquad \text{and} \tag{1.2}$$

$$G_{\mathrm{EWK}} = \mathrm{SU}(2)_L \times \mathrm{U}(1)_Y, \tag{1.3}$$

corresponding to the *strong* and *electroweak* interactions, respectively. Each fermion field exists in a unique representation of G_{SM}, also summarized in Table 1.1. The possible represenations of $\mathrm{SU}(3)_C$ are triplet, conjugate, and singlet, denoted by **3**, $\bar{\mathbf{3}}$, and **1**, respectively, while the possible representations of $\mathrm{SU}(2)_L$ are doublet and singlet, denoted by **2** and **1**, respectively. All fermions exist in the singlet represen-

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tation of $U(1)_Y$, only distinguished by differing values of the weak hypercharge Y. Conversely, all fermions in non-singlet representations of $SU(3)_C$ and $SU(2)_L$ have the same interaction strength, a feature known as universality.

Table 1.1: The categories of SM fermions and the action of the SM local gauge symmetry group G_{SM}. Each category contains three members, one for each generation of the Standard Model. A corresponding table exists for the charge conjugated fields representing the anti-fermions. The subscripts L and R denote whether the field is left- or right-handed.

Name	Symbol	Y	$SU(2)_L$ rep.	$SU(3)_C$ rep.
Left-handed quark	q_L	$1/6$	**2**	**3**
Right-handed up-type quark	u_R	$2/3$	**1**	**3**
Right-handed down-type quark	d_R	$-1/3$	**1**	**3**
Left-handed lepton	ℓ_L	$-1/2$	**2**	**1**
Right-handed charged lepton	e_R	-1	**1**	**1**
Right-handed neutrino	ν_R	$1/6$	**1**	**1**

For each category of fermion listed in Table 1.1, there exist three generations or copies in the Standard Model, identical except for differing masses. The lepton electroweak doublets contain the left-handed charged leptons and neutrinos

$$\ell_L = \begin{pmatrix} \nu_e \\ e_L^- \end{pmatrix}, \begin{pmatrix} \nu_\mu \\ \mu_L^- \end{pmatrix}, \begin{pmatrix} \nu_\tau \\ \tau_L^- \end{pmatrix}, \tag{1.4}$$

and the right-handed lepton singlets contain the right-handed projections of the same leptons and neutrinos. The quark electroweak doublets contain the left-handed up-type and down-type quarks

$$q_L = \begin{pmatrix} u_L \\ d_L \end{pmatrix}, \begin{pmatrix} c_L \\ s_L \end{pmatrix}, \begin{pmatrix} t_L \\ b_L \end{pmatrix}, \tag{1.5}$$

and the right-handed quark singlets contain the right-handed projections of the same quarks. Quarks also exist in a strong triplet, which will be denoted with a superscript c as necessary.

1.1.1 Strong Interactions

The strong interactions of quarks and gluons are described by quantum chromodynamics (QCD), with the Lagrangian

$$\mathcal{L}_{\text{QCD}} = i\bar{q}_f^a \slashed{D}^{ab} q_f^b + m_f \bar{q}_f^a q_f^a - \frac{1}{4} G_{\mu\nu}^a G^{a,\mu\nu} + \theta \frac{g_s^2}{72\pi^2} \epsilon_{\mu\nu\rho\sigma} G^{c,\mu\nu} G^{c,\rho\sigma}, \qquad (1.6)$$

where repeated indices are contracted. The q_f^a are the quark-field Dirac spinors of flavor $f \in \{u,d,c,s,t,b\}$, color $a \in \{r,g,b\}$ (he basis element of the triplet representation), and mass m_f. The first term in Equation 1.6 contains the QCD covariant derivative

$$D_\mu^{ab} = \delta^{ab}\partial_\mu - ig_s \sum_c t_c^{ab} G_{c,\mu}, \qquad (1.7)$$

where g_s is the strong interaction coupling strength, t_c are the eight 3×3 Hermitian traceless matrices that serve as the generators of the triplet representation of $\text{SU}(3)_C$, and G_c are the corresponding eight gluon fields. The third term in Equation 1.6 contains the gluon field strength tensors

$$G_{\mu\nu}^a = \partial_\mu G_\nu^a - \partial_\nu G_\mu^a - g_s f^{abc} G_\mu^b G_\nu^C, \qquad (1.8)$$

where f^{abc} are the structure constants of $\text{SU}(3)_C$. The non-Abelian structure of the $\text{SU}(3)_C$ group means allows for 3-gluon and 4-gluon interactions in addition to the quark-antiquark-gluon interactions.

The last term in Equation 1.6 violates CP conservation and produces a non-zero electric dipole moment (EDM) for the neutron. Experimental limits on the neutron EDM constraint the θ parameter to be smaller than 10^{-10}. The Peccei-Quinn theory provides a possible method to force θ to zero by introducing the hypothetical axion particle. The axion is a potential dark matter candidate and will be discussed further in Section **??**.

1.1.2 Electroweak Interactions

The electroweak interactions of fermions are described by $\mathrm{SU(2)}_L \times \mathrm{U(1)}_Y$ gauge group, with the Lagrangian

$$\mathcal{L}_{\mathrm{EWK}} = i\bar{\psi}_i \slashed{D}\psi_i - \frac{1}{4}\vec{W}_{\mu\nu} \cdot \vec{W}^{\mu\nu} - \frac{1}{4}B_{\mu\nu}B^{\mu\nu} \tag{1.9}$$

where repeated indices are contracted and $\psi \supseteq \{q_L, u_R, d_R, \ell_L, e_R, \nu_R\}$ is the set of SM fermions, and the gauge field tensors are given by

$$B_{\mu\nu} = \partial_\mu B_\nu - \partial_\nu B_\mu \qquad \text{and} \tag{1.10}$$

$$\vec{W}_{\mu\nu} = \partial_\mu \vec{W}_\nu - \partial_\nu \vec{W}_\mu + g\vec{W}^\mu \times \vec{W}^\nu, \tag{1.11}$$

where $\vec{W}_\mu$ and B_μ are the gauge fields for $\mathrm{SU(2)}_L$ and $\mathrm{U(1)}_Y$, respectively, and g is the coupling strength for $\mathrm{SU(2)}_L$. The first term in Equation 1.9 contains the EWK covariant derivative

$$D_\mu = \partial_\mu - ig\vec{T} \cdot \vec{W}_\mu - ig'Y B_\mu, \tag{1.12}$$

where g' is the coupling strength for $\mathrm{U(1)}_Y$, Y is the $\mathrm{U(1)}_Y$ hypercharge of the fermion field, and $\vec{T}$ are the generators of the doublet representation of $\mathrm{SU(2)}_L$. The generators can be written in terms of the Pauli spin matrices $\vec{T} = \vec{\sigma}/2$ and only have non-zero action on left-handed particles. The values of the hypercharge Y shown in Table 1.1 are chosen such that the physical electric charge of each fermion is given by $Q = T_3 + Y$.

Notice that Equation 1.9 does not contain a Dirac mass term like that found in Equation 1.6. This is because the term

$$m\bar{\psi}\psi = m\left(\bar{\psi}_L\psi_R + \bar{\psi}_R\psi_L\right) \tag{1.13}$$

mixes the left-handed and right-handed fermions leading to a Lagrangian that is no longer invariant under $\mathrm{SU(2)}_L$. As the observed fermions are not massless, the Lagrangian given in Equation 1.9 is incomplete and an additional mechanism needs to be introduced to produce non-zero fermion masses.

1.1.3 Electroweak Symmetry Breaking

Spontaneous electroweak symmetry breaking provides the mechanism we need, as well as providing masses to the weak gauge bosons. The $SU(2)_L$ symmetry is broken by introducing a left-handed complex scalar doublet ϕ with $Y_\phi = 1/2$ to the Lagrangian in the following manner

$$\mathcal{L}_{\text{EWK}} \mapsto \mathcal{L}_{\text{EWK}} + |D_\mu \phi|^2 + \mu^2 \phi^2 - \lambda |\phi|^4. \tag{1.14}$$

We choose to write this complex doublet, known as the complex Higgs field, in terms of four real-valued fields so that

$$\phi = \frac{1}{\sqrt{2}} \begin{pmatrix} \phi_1 + i\phi_2 \\ \phi_3 + i\phi_4 \end{pmatrix}. \tag{1.15}$$

Fortunately, the two self-interaction terms create a Higgs potential with a degenerate global minimum at the vacuum expectation value (vev)

$$v \equiv \langle |\phi| \rangle = \sqrt{\frac{\mu^2}{\lambda}}, \tag{1.16}$$

and through gauge rotations we set $\langle \phi_{1,2,4} \rangle = 0$, removing three degrees of freedom and producing three massless Nambu-Goldstone bosons. The remaining degree of freedom is the real Higgs field H which expresses small peturbations around the vev in the third component of the complex Higgs field $\phi_3 = v + H$.

The kinetic term in Equation 1.14 couples the complex Higgs field to the EWK gauge bosons as follows at the vev

$$|D_\mu \phi|^2 = \frac{v^2}{8} \left[\left(g W_\mu^1 \right)^2 + \left(g W_\mu^2 \right)^2 + \left(g' B_\mu - g W_\mu^3 \right)^2 \right]. \tag{1.17}$$

Diagonalizing this term gives rise to the three massive weak bosons and the massless photon that we observe in nature:

$$
\begin{array}{l|l}
W_\mu^\pm \equiv \frac{1}{\sqrt{2}} \left(W_\mu^1 \mp W_\mu^2 \right) & m_W = \frac{1}{2} v g \\[4pt]
Z_\mu \equiv \cos\theta_{\mathrm{W}} W_\mu^3 - \sin\theta_{\mathrm{W}} B_\mu & m_Z = \frac{1}{2} v \sqrt{g^2 + (g')^2} \\[4pt]
A_\mu \equiv \sin\theta_{\mathrm{W}} W_\mu^3 + \cos\theta_{\mathrm{W}} B_\mu & m_A = 0,
\end{array}
\tag{1.18}
$$

where $\tan\theta_{\mathrm{W}} = g'/g$. With this, we rewrite Equation 1.9 in terms of the observed electromagnetic, charged weaked, and neutral weak currents as follows:

$$
\mathcal{L}_{\mathrm{EWK}} = \bar\psi_i \left(i\slashed\partial - e Q \slashed A \right) \psi_i - \frac{g}{2\sqrt{2}} \bar\psi_i \left(T^+ \slashed W^+ + T^- \slashed W^- \right) \psi_i
\tag{1.19}
$$

$$
- \frac{g}{2\cos\theta_{\mathrm{W}}} \bar\psi_i (g_V - g_A \gamma^5) \slashed Z \psi_i,
\tag{1.20}
$$

where $e = g' \cos\theta_{\mathrm{W}}$ is the charge of the electron, $T^\pm = (T_1 \mp i T_2)/\sqrt{2}$ are the weak isospin raising and lowering operators, and $g_V = T_3$ and $g_A = T_3 - 2Q\sin^2\theta_{\mathrm{W}}$ are the vector and axial-vector couplings for the neutral weak current.

We can also expand Equation 1.14 about the vev giving us the following Higgs Lagrangian

$$
\mathcal{L}_H = \frac{1}{2} \partial_\mu H \partial^\mu H - \frac{1}{2} m_H^2 H^2 - \frac{1}{2} m_W^2 W_\mu^+ W^{-\mu} - \frac{1}{2} m_Z^2 Z_\mu Z^\mu
\tag{1.21}
$$

$$
+ \frac{m_H^2}{2v} H^3 + \frac{2 m_W^2}{v} W_\mu^+ W^{-\mu} H + \frac{m_Z^2}{v} Z_\mu Z^\mu H
\tag{1.22}
$$

$$
+ \frac{m_H^2}{8v^2} H^4 + \frac{m_W^2}{v^2} W_\mu^+ W^{-\mu} H^2 + \frac{m_Z^2}{2v^2} Z_\mu Z^\mu H^2,
\tag{1.23}
$$

where $m_H = \mu\sqrt{2}$. Thus, we see that the real Higgs field H has trilinear and quartic couplings to itself and the weak gauge bosons with coupling strengths proportional to the mass squared of the appropriate boson. This suggests a way to introduce fermion masses through the Higgs field.

1.1.4 Fermion Masses

Introducing Yukawa couplings between the complex Higgs field ϕ and the SM fermion fields enables us to add mass terms for the fermions. First, we start with the terms for charged leptons,

$$\mathcal{L}_Y^{\text{leptons}} = -\bar{\ell}_L Y_e \phi e_R - \bar{e}_R Y_e \phi^\dagger \ell_L, \tag{1.24}$$

where Y_e is the Yukawa matrix for the charged leptons. In general, Yukawa matrices and thus mass matrices are non-diagonal and hence we need to convert from the electroweak eigenstates $f_{L,R}$ to the mass eigenstates $\tilde{f}_{L,R} = U_{L,R}^f f_{L,R}$ where $U_{L,R}^f$ is a unitary matrix. With this we rewrite Equation 1.24 in terms of the mass eigenstates

$$\mathcal{L}_Y^{\text{leptons}} = -\bar{\tilde{\ell}}_L U_L^e Y_e \phi U_R^{e\dagger} \tilde{e}_R - \bar{\tilde{e}}_R U_R^e Y_e \phi^\dagger U_L^{e\dagger} \tilde{\ell}_L \tag{1.25}$$

$$= -\bar{\tilde{\ell}}_L \tilde{Y}_e \phi \tilde{e}_R - \bar{\tilde{e}}_R \tilde{Y}_e^\dagger \phi^\dagger \tilde{\ell}_L, \tag{1.26}$$

where $\tilde{Y}_e = U_L^e Y_e U_R^{e\dagger}$ is the diagonalized Yukawa matrix for the charged leptons. After electroweak symmetry breaking, these terms become

$$\mathcal{L}_Y^{\text{leptons}} = -\frac{v+H}{\sqrt{2}} \left(\bar{\tilde{e}}_L \tilde{Y}_e \tilde{e}_R + \bar{\tilde{e}}_R \tilde{Y}_e^\dagger \tilde{e}_L \right) \tag{1.27}$$

$$= -\left(1 + \frac{H}{v} \right) \left(\bar{\tilde{e}}_L \tilde{M}_e \tilde{e}_R + \bar{\tilde{e}}_R \tilde{M}_e^\dagger \tilde{e}_L \right) \tag{1.28}$$

$$= -\tilde{M}_e \bar{e} e - \frac{\tilde{M}_e}{v} \bar{e} e H, \tag{1.29}$$

where $\tilde{M}_e = v\tilde{Y}_e/\sqrt{2}$ is the diagonalized mass matrix for the charged leptons and e is the set of massive Dirac spinors for the charged leptons.

From Equation 1.29, we see that the Yukawa couplings between the complex Higgs field ϕ and the charged leptons result in a Dirac mass term and a coupling to the real Higgs field H that is proportional to the mass of the charged leptons and the vev. The same procedure is used to introduce mass terms for the down-type quarks whereas for the neutrinos and up-type quarks we must use the conjugate doublet $\phi_c = -i\sigma_2 \phi^*$ in place of ϕ to obtain the same result.

1.1.5 Flavor Mixing

For the charged leptons and up-type quarks, it is possible to define a basis of simultaneous electroweak and mass eigenstates, so in practice $\tilde{Y}_{e,u} = Y_{e,u}$ as $U_L^{e,u} = U_R^{e,u} = \mathbf{I}$. However, it is not possible to do this for the neutrinos at the same time as the charged leptons or for the down-type quarks at the same time as the up-type quarks.

When writing Equation 1.19 in terms of the mass eigenstates, the charged current term involves interactions between the up-type and down-type quarks:

$$\mathcal{L}_{\text{CC}} = -\frac{g}{2\sqrt{2}} \left(\bar{u}_L T^+ W\!\!\!/\,^+ d_L + \bar{d}_L T^- W\!\!\!/\,^- u_L \right) \tag{1.30}$$

$$= -\frac{g}{2\sqrt{2}} \left(\bar{\tilde{u}}_L U_L^{u\dagger} T^+ W\!\!\!/\,^+ U_L^d \tilde{d}_L + \bar{\tilde{d}}_L U_L^{d\dagger} T^- W\!\!\!/\,^- U_L^u \tilde{u}_L \right) \tag{1.31}$$

$$= -\frac{g}{2\sqrt{2}} \left(\bar{\tilde{u}}_L T^+ W\!\!\!/\,^+ V_{\text{CKM}} \tilde{d}_L + \bar{\tilde{d}}_L T^- W\!\!\!/\,^- V_{\text{CKM}}^\dagger \tilde{u}_L \right), \tag{1.32}$$

where $V_{\text{CKM}} = U_L^{u\dagger} U_L^d$ is the Cabibbo-Kaboyshi-Maskawa matrix. The CKM matrix is unitary with four free parameters, the mixing angles between quark generations ϕ_{12}, ϕ_{23}, and ϕ_{13} as well as a CP-violating phase δ. In terms of these parameters, the CKM matrix is

$$V_{\text{CKM}} = \begin{pmatrix} c_{12} & s_{12} & 0 \\ -s_{12} & c_{12} & 0 \\ 0 & 0 & 1 \end{pmatrix} \times \begin{pmatrix} 1 & 0 & 0 \\ 0 & c_{23} & s_{23} \\ 0 & -s_{23} & c_{23} \end{pmatrix} \times \begin{pmatrix} c_{13} & 0 & s_{13}e^{-i\delta} \\ 0 & 1 & 0 \\ -s_{13}e^{i\delta} & 0 & c_{13} \end{pmatrix}, \tag{1.33}$$

where $s_{ij} = \sin\phi_{ij}$ and $c_{ij} = \cos\phi_{ij}$. It has been experimentally determined that the CKM is mostly diagonal with $s_{13} \ll s_{23} \ll s_{12} \ll 1$.

The equivalent mixing matrix for the neutrinos is the Pontecorvo-Maki-Nakagawa-Sakata matrix U_{PMNS}, which converts from the mass eigenstates ν_1, ν_2, and ν_3 to the electroweak eigenstates ν_e, ν_μ, ν_τ. Unlike the CKM matrix, the PMNS is non-diagonal resulting in stronger mixing in the neutrino sector. The values of the mixing angles θ_{12}, θ_{23}, and θ_{13} have been measured in neutrino oscillation experiments while the CP-violating phase δ' has not yet been directly measured. From cosmological measurements, it is known that the sum of the neutrino masses is less than one eV.

1.1.6 Summary

The Standard Model has a total of 26 free parameters and 17 physical particles. The particles and their properties are summarized in Table 1.2 and the parameters are the twelve Yukawa couplings for the fermions, the four parameters of the CKM matrix, the four parameters of the PMNS matrix, the three coupling constants g_s, g, and g', the Higgs vacuum expectation value v, the Higgs self-coupling λ, and the CP-violating θ parameter of QCD Lagrangian.

Table 1.2: The physical particles of the Standard Model.

Name	Symbol	Spin	Charge	Mass
up quark	u	½	⅔	2.2 MeV
down quark	d	½	-⅓	4.7 MeV
charm quark	c	½	⅔	1.28 GeV
strange quark	s	½	-⅓	95 MeV
top quark	t	½	⅔	173 GeV
bottom quark	b	½	-⅓	4.18 GeV
electron neutrino	ν_e	½	0	-
electron	e	½	-1	511 keV
muon neutrino	ν_μ	½	0	-
muon	μ	½	-1	105 MeV
tau neutrino	ν_τ	½	0	-
tau	τ	½	-1	1.78 GeV
gluon	g	1	0	0
photon	γ	1	0	0
Z boson	Z	1	0	91.2 GeV
W boson	$W^\pm$	1	±1	80.4 GeV
Higgs boson	H	0	0	125 GeV