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Search Prospect for Extremely Weakly-Interacting Particles at the Gamma Factory

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The Gamma Factory is a proposal to back-scatter laser photons off a beam of partially-stripped ions at the LHC, producing a beam of $\sim$ 10 MeV to 1 GeV photons with intensities of 10^{16} to 10^{18} s^{-1}. This implies $\sim$ 10^{23} to 10^{25} photons on target per year, many orders of magnitude greater than existing accelerator light sources and also far greater than all current and planned electron and proton fixed target experiments. We discuss the Gamma Factory's discovery potential through "dark Compton scattering," $\gamma e \to eX$, where X is a new, weakly-interacting particle. For dark photons and other new gauge bosons with masses in the 1 to 100 MeV range, the Gamma Factory has the potential to discover extremely weakly-interacting particles with just a few hours of data-taking and will probe new physics couplings as low as $\sim 10^{-9}$ with a year of data-taking. The Gamma Factory therefore may probe couplings lower than all other terrestrial experiments and is highly complementary to astrophysical probes. We outline the requirements of an experiment to realize this potential and determine the sensitivity reach for various experimental configurations.

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Introduction The search for new light and weakly-interacting particles is currently an area of great interest. If new particles have masses in the MeV to GeV range, they cannot be coupled to the known particles with $O(1)$ couplings. The existence of such particles is an open experimental question, and novel searches for such particles should be explored, particularly if they exploit existing facilities.

The Gamma Factory (GF) is such an initiative, which exploits the Large Hadron Collider (LHC) [1, 2]. In this proposal, laser light with energy $E_{\text{laser}} \sim 10$ eV is back-scattered off partially-stripped ions that are accelerated in the LHC to Lorentz factors $\gamma \sim 200$ to 3000. Using the same principle that governs radar guns, the laser light is Doppler shifted twice to energies $E_{\text{GF}} \sim 10$ MeV − 1 GeV. These energies are well-matched to the MeV to GeV mass range for new, weakly-interacting particles. The expected intensities of $\Phi_{\text{GF}} \sim 10^{16}$ to $10^{18}\ \text{s}^{-1}$ are far greater than any other existing or proposed accelerator light source, and the resulting number of GF photons per year, $N_{\text{GF}} \sim 10^{23}$ to 10^{25}, is significantly greater than the protons on target and electrons on target of all fixed target experiments used to search for new MeV to GeV particles to date. The GF, then, has the potential to explore models with light, weakly-interacting particles in regions of parameter space inaccessible to other experiments.

In Ref. [3], we determine the GF's discovery potential for a variety of new, weakly-interacting particles X produced through dark Compton scattering, $\gamma e \to eX$. Our results provide a significant new physics case for the GF, supplementing existing SM and beyond the SM motivations [4].

A Fixed Target Experiment The fixed target experiment we propose is simple, compact, and not particularly remarkable; it is shown schematically in Fig. 1. The details of the required materials and thickness of the target and shield can be found in Ref. [3].

Taking the photon intensity to be $\Phi_{\text{GF}} = 10^{17}\ \text{s}^{-1}$ [1, 2] at 200 MeV, we consider three sets of parameters:

$$\begin{aligned} &E_\gamma = 20\ \text{MeV},\ \ \Phi_{\text{GF}} = 10^{18}\text{s}^{-1};\ N_{\text{GF}} = 3\times10^{25} \\ &E_\gamma = 200\ \text{MeV},\ \Phi_{\text{GF}} = 10^{17}\text{s}^{-1};\ N_{\text{GF}} = 3\times10^{24} \\ &E_\gamma = 1.6\ \text{GeV},\ \ \Phi_{\text{GF}} = 10^{16}\text{s}^{-1};\ N_{\text{GF}} = 3\times10^{23}; \end{aligned} \tag{1}$$

where the lowest photon energy is based on a longer laser wavelength or lower ion energy, the highest photon energy would be possible with the HE-LHC project [5], and, in each case, N_{GF} is simply the number of photons produced in a full year at the corresponding intensity.

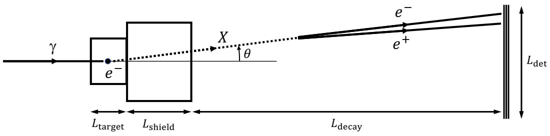

Figure 1: Experiment layout. *The experiment consists of a (graphite) target with thickness $L_{target} = 1$ m, followed by a (lead) shield with thickness $L_{shield} = 2$ m, an open air decay region with length L_{decay}, and a tracking detector, centered on the beam axis, which we take to be a circular disk with diameter L_{det}. The GF photon beam enters from the left and produces an X particle through dark Compton scattering $\gamma e \to eX$. The X particle is produced with an angle θ relative to the GF beamline and decays to an e^+e^- pair, which is detected in the tracking detector.*

Dark Photons We first consider the case where the new, weakly-interacting particle is the dark photon A' [6]. The dark photon's properties are determined by two parameters, its mass $m_{A'}$ and its coupling ε (in units of e). The cross section for dark Compton scattering $\gamma e \to eA'$ and the angular distribution of the produced dark photons are shown in Fig. 2. (See the Appendix of Ref. [3] for further details.)

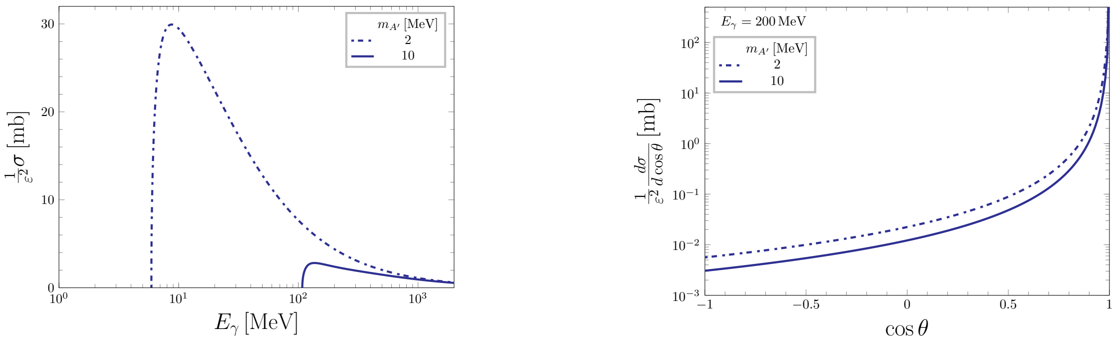

Figure 2: **Left**: *Dark photon production cross section $\sigma(\gamma e \to eA')$ as a function of incoming photon energy E_γ for $m_{A'} = 2, 10$ MeV.* **Right**: *Lab frame angular differential distribution of dark photons A′ produced through dark Compton scattering, where θ is the angle relative to the photon beam line (see Fig. 1), $E_\gamma = 200$ MeV, and $m_{A'} = 2, 10$ MeV.*

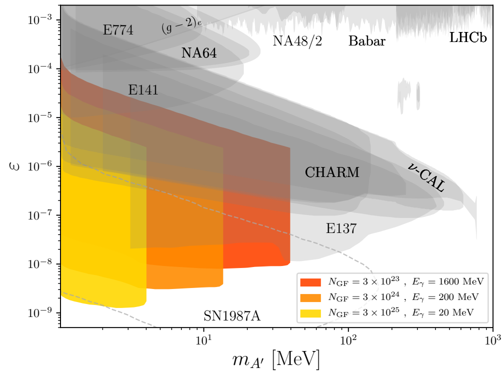

Figure 3: **Dark photon sensitivity.** *The sensitivity reach for the three sets of (E_γ, N_{GF}), each corresponding to a year of data-taking, and detector parameters $L_{decay} = 12$ m and $L_{det} = 3$ m. The contours are for 3 e^+e^- signal events assuming no background. The coloured areas are the regions that can be probed at the GF. The gray regions are existing bounds from the terrestrial experiments (see Ref.[38-53] in the caption of FIG. 3 in Ref. [3]), and the dashed gray line encloses the region probed by supernova cooling [7].*

Once produced, the dark photon dominantly decays to pairs of SM particles, assuming $m_{A'} > 2m_e$. For $m_{A'} > 2m_\mu$, decays to a pair muons or to a number of hadronic states are possible. However, given the available GF energies of Eq. (1), $m_{A'} \lesssim 40$ MeV, only the decay channel $A' \to e^+e^-$ is open. To determine the sensitivity reach, for any parameters $(m_{A'}, \varepsilon)$, we simulate dark photon production by dark Compton scattering, including the correct $\cos\theta$ distribution. For a given point in parameter space, i.e., for a fixed pair of X mass and coupling, we randomly extract 10^5 values of $\cos\theta$ from the inverse of the cumulative distribution function:

$$\mathcal{P}(\cos\theta) = \frac{\int_{-\cos\theta}^{\cos\theta} \overline{|\mathcal{M}|^2}}{\int_{-1}^{1} \overline{|\mathcal{M}|^2}} \in [0, 1]\,, \qquad (2)$$

$\overline{|\mathcal{M}|^2}$ being the spin-averaged matrix element of the dark Compton scattering process. From the obtained distribution of $\cos\theta$, we derive the distribution of the signal events, $\mathcal{P}(N_S)$. In particular, after checking that the simulated $e^\pm$ pairs pass through the detector, we can compute the mean of events $\langle N_S \rangle$. If $\langle N_S \rangle \geq 3$ events, we accept the chosen point in parameter space as one within the GF sensitivity. In any other case, we discard it. A signal event is indeed defined to be an event where both the e^+ and the $e-$ pass through the tracking detector shown in Fig. 1. The coincident detection of two oppositely charged particles, each pointing back to the target, will be a striking signal, and we will assume zero background.

The results shown in Fig. 3 may be understood as follows: The sensitivity regions are bounded at low mass by the requirement that the e^+e^- decay is open ($m_{A'} > 2m_e$) and at high mass by the requirement that dark Compton scattering $\gamma e \to eX$ is kinematically accessible ($m_{A'} \lesssim \sqrt{2m_e E_\gamma}$). The regions are further bounded at large ε by the requirement that the dark photons travel through the target and shield before decaying ($d_{A'} \gtrsim 3$ m), and at small ε by the requirement that a sufficient number of dark photons decay in the decay volume. We see that, provided the beam energy is above threshold, the number of events is approximately independent of $m_{A'}$, but is highly sensitive to ε. One also expects to probe ε as low as 10^{-9}, given the large number of GF photons on target.

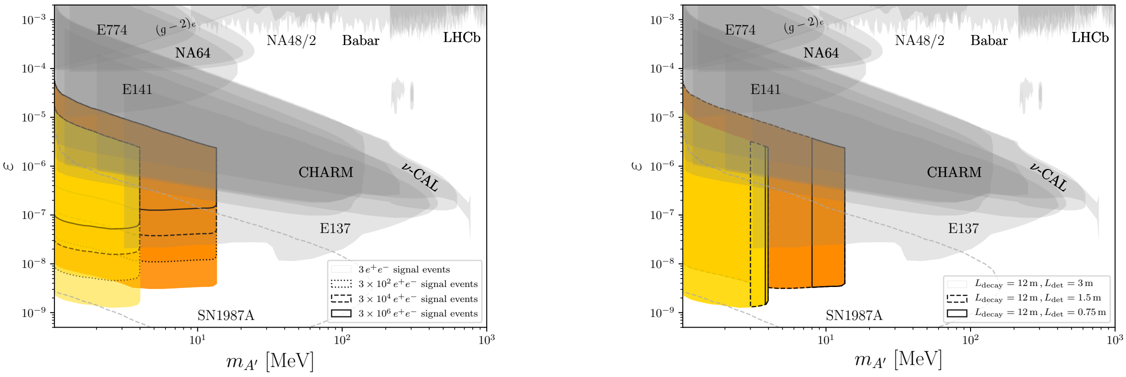

Figure 4: Left: *Event rate contours for* $(E_\gamma, N_{GF}) = (20\,MeV, 3\times10^{25})$ *(yellow) and* $(E_\gamma, N_{GF}) = (200\,MeV, 3\times10^{24})$ *(orange),* $L_{decay} = 12\,m$*, and* $L_{det} = 3\,m$. **Right:** *The sensitivity reach for* $(E_\gamma, N_{GF}) = (20\,MeV, 3\times10^{25})$ *(yellow) and* $(E_\gamma, N_{GF}) = (200\,MeV, 3\times10^{24})$ *(orange),* $L_{decay} = 12\,m$*, and* $L_{det} = 0.75$*, 1.5, and 3 m. The contours are for 3* e^+e^- *signal events assuming no background. The coloured areas are the regions that can be probed at the GF. The gray regions and dashed gray line are existing constraints from terrestrial experiments and supernovae, respectively, as in Fig. 3.*

In the left panel of Fig. 4, we show signal event rate contours for the GF parameters $(E_\gamma, N_{\rm GF}) = (20\text{ MeV}, 3\times10^{25})$ (yellow) and $(E_\gamma, N_{\rm GF}) = (200\text{ MeV}, 3\times10^{24})$ (orange). In the right panel of Fig. 4, we show the dependence of the sensitivity reach on the size of the detector $L_{\rm det}$.

The GF also has significant potential to discover other anomaly-free light gauge bosons. The analysis go in the similar line as above. For completeness, we also considered two spin-0 dark mediator particles [8, 9]: the dark Higgs boson and the dark pseudoscalar. We skip that detail here for economy of space. Interested readers can go through detail analysis in Ref. [3].

Conclusions The proposed GF will be able to provide 10^{23} to 10^{25} photons on target per year, a remarkable leap in light source intensity. By exploiting the LHC's ability to accelerate partially-stripped ions to Lorentz factors of $\gamma\sim$ 200-3000, $\sim$ 10 eV photons can be back-scattered to 10 MeV to GeV energies, sufficient to search for new particles with masses in the 1-100 MeV mass range.

We have investigated for the first time the potential of the GF to discover new particles through dark Compton scattering, $\gamma e \to eX$, where X is a dark photon. The same formalism can be extended to anomaly-free gauge boson, dark Higgs boson, or dark pseudoscalar [3]. In the cases of the spin-1 gauge bosons, we have found that the extraordinary intensities of the GF allow it to probe couplings as low as $\varepsilon\sim10^{-9}$, over an order of magnitude lower than existing bounds from terrestrial experiments. The ε^4 dependence of the signal event rate implies that as many as 10^4 new gauge bosons may be produced in a year at the GF, or, in other words, the GF may start probing new models with just a few hours of data-taking. The region of parameter space with couplings $\varepsilon\sim10^{-9}$ can be probed by bounds from supernova cooling [10, 11], but such constraints depend on astrophysical assumptions that have been argued to weaken or possibly even be irrelevant altogether [12]. The GF therefore provides a highly complementary probe.

We have assumed that the detection of coincident e^+ and e^- particles that point back toward the GF photon beam, with an invariant mass equal to the X boson's mass, will provide a spectacular and essentially background-free signal.

As we discussed in Ref [3], for the spin-0 candidates, with Yukawa-suppressed couplings to SM fermions, the discovery prospects is poor, since the signal rates are highly suppressed by the GF's dependence on the couplings of new X particles to electrons. For such models, GF photons scattering off nucleons and nuclei, instead of electrons, may provide significantly improved prospects. Finally, we have considered only a small sample of the many possible new light, weakly-interacting particles. Axion-like particles have recently been considered [13], and evaluations of the GF sensitivity reach to other particles, such as sterile neutrinos, may also be enlightening.

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