A Milli-Charged Particle Detector at LHC P5

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We propose a dedicated experiment that would detect milli-charged particles produced by pp collisions at LHC Point 5. The experiment would be installed during LS2 in the vestigial drainage gallery above UXC and would not interfere with CMS operations. With 300 fb^{-1} of integrated luminosity, sensitivity to a particle with charge $\mathcal{O}(10^{-3})\ e$ can be achieved for masses of $\mathcal{O}(1)$ GeV, and charge $\mathcal{O}(10^{-2})\ e$ for masses of $\mathcal{O}(10)$ GeV, greatly extending the parameter space explored for particles with small charges and masses above 100 MeV.

1 Introduction

We propose a dedicated experiment to search for milli-charged particles (mCP). The proposed experiment is a model-independent probe of mCPs, since it relies only on the masses and charges of such particles. One can view this search as part of a general program to search for additional sectors. A prototypical model of milli-charged particles [14] consists of an abelian gauge field A'_μ that couples to a massive Dirac fermion ψ of mass M_{mCP} and to hypercharge via kinetic mixing. A simple field redefinition removes the kinetic mixing, yielding the Lagrangian

$$\mathcal{L} = \mathcal{L}_{\text{SM}} - \frac{1}{4}A'_{\mu\nu}A'^{\mu\nu} + i\bar{\psi}\left(\partial\!\!\!/ + ie'A\!\!\!/' - i\kappa e' B\!\!\!/ + iM_{\text{mCP}}\right)\psi.$$

The new matter field ψ therefore has an electric charge of $\epsilon \equiv \kappa e' \cos\theta_W / e \ll 1$, a milli-charge. The parameter space spanned by the mass and charge of the mCPs is constrained by indirect observations [7, 8, 9, 10, 11, 15, 18], although these can often be evaded by adding extra degrees of freedom. Previous experiments have also looked for non-quantized charged particles [5, 6, 8, 16]. However, the parameter space for mCPs with masses $0.1 \lesssim M_{\text{mCP}} \lesssim 100$ GeV and charges at the $10^{-3}\ e - 10^{-1}\ e$ level is largely unexplored by direct searches. In particular, the CMS/ATLAS sensitivity to mCPs in monojet and missing energy searches is precluded by the penalty on the cross-section associated with initial state radiation. In the following, we summarize a recent proposal [4, 12] to construct a dedicated detector at the LHC to target this unexplored part of parameter space.

2 Overview of the Experiment

The experimental apparatus envisaged is 3 scintillator detector layers of roughly 1 m^3 each, positioned near one of the high-luminosity interaction points of the LHC. LHC Point 5 (Cessy) is host to the Compact Muon Solenoid (CMS) experiment and its supporting infrastructure. As such, the appropriate services - electricity, ethernet, LHC luminosity information - would be available. We propose that the detector be set in the PX56 drainage gallery located above CMS UXC. In Figure 1, a 3D model was combined with a laser scan of the gallery to give a best as-built estimation. An optimal position was found which offered a distance to the IP of 33 m at an angle of 43.1 degrees from the horizontal plane, 17 m of which is through rock. The size of the drainage gallery constrains the length of the detector, but not the sides. Hence there is space to install shielding and forced air cooling.

We are also engineering a system to rotate the detector to a stowed position during access periods. This proposal has already been run through various LHC and CMS operation bodies and no conflicts were identified. The detector itself is a 1 m $\times$ 1 m $\times$ 3 m plastic scintillator array, oriented to point to the CMS interaction point. The array is subdivided into 3 sections each containing 400 5 cm $\times$ 5 cm $\times$ 80 cm scintillator bars optically coupled to high-gain PMTs. A minimum-ionizing particle of charge Q leaves roughly $2Q^2$ MeV/cm in a material of density 1 g/cm^3. We therefore expect an average of $\mathcal{O}(1)$ photoelectron (PE) from each PMT for mCPs of charge $Q = \mathcal{O}(10^{-3})$ e [4]. Requiring a longitudinal triple-incidence within a 15 ns time window amounts to $\mathcal{O}(10)$ events per year with $N_{\mathrm{PE}} \geq 1$.

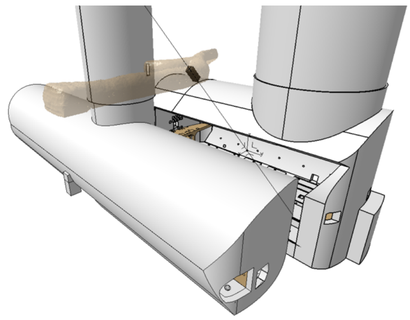

Figure 1: A 3D model with the optimal position of milliQan above CMS UXC.

3 Backgrounds

The dominant background is dark-current in the PMTs. Additional sub-dominant sources of background include activity in the scintillator from background radiation and photo-multiplier after-pulsing. To measure the dark-current, we constructed a test setup using a 3" Bicron-412 scintillator coupled to a 3" Hamamatsu H2431 PMT at 3 kV, readout with a CAEN V1743 digitizer, described in Section 4. Once the board receives a triggering event, the analog buffer is digitized. During this digitization window, which lasts approximately 100 μs, no additional trigger can be accepted. Using this test setup, we measured a dark-current rate of approximately 1 kHz at room temperature. By reducing the high voltage and cooling the PMT we are able to significantly reduce the background rate. With these handles we expect to be able to bring the rate to below 500 Hz. Another source of background are cosmic and LHC muons, which consist of >1000 PEs. We measured the PMT rates in a counting room close to our proposed location. Collecting data with/without the LHC beam, as well as with/without led and polyethylene shielding, we found that the PMT rates with shielding become comparable to the dark-current rates, and hence we don't expect muons to create too much activity and after-pulses in our scintillators. If a muon does hit the detector, it can be easily vetoed offline by its large pulse.

4 Data Acquisition

Analog pulses from the PMTs must be digitized and stored for offline analysis. Furthermore, a trigger will record only those pulses during interesting time windows when significant activity in the detector is observed. This can all be performed for modest cost using the CAEN V1743 digitizer. This digitizer board has 16 channels, each of which is sampled into 7 analog buffers. The digitization is done with 12 bits of precision, and the dynamic range is 2.5 V, allowing good resolution of 0.61 mV. Analog noise is about 0.75 mV per channel, whereas single PE signals can easily be above 3 mV. The only drawback of the analog buffer approach is that the board is dead while digitizing the buffer. This results in a deadtime of $\lesssim 10$ %. However, the time after a trigger is anyways of low quality due to the presence of PMT after-pulses. Thus there is no dead time from readout, up to rates of ~ 1 kHz. For the triggering, we will connect 12 PMTs (2×2/layer, aligned longitudinally) to one board. Two neighbouring PMTs in each layer will form a group. The whole detector will be read out if any two groups in a board are above threshold within a time window of $(\Delta t)_{\text{online}} = 100$ ns. Given PMT dark-current rates of 500 Hz, the trigger rate is expected to be 75 Hz [4]. Offline we will tighten the time window to $(\Delta t)_{\text{offline}} = 15$ ns. The total offline background rate is estimated to be 1.1×10^{-5} Hz. The LHC will have delivered 300 fb^{-1} during Run 3 (3000 fb^{-1} during HL-LHC). We therefore estimate to have 165 (330) background events [4]. We expect to use pulse shapes and expected arrival time of particles produced in the LHC to reduce the total background to ~ 50 (100) events.

5 Simulations and Sensitivity

In order to evaluate the projected sensitivity of the experiment for various mCP electric charges and masses, we performed a full simulation of the experiment, including a GEANT4 [1] model of the detector. In the first stage, MADGRAPH5 and MADONIA were used to simulate the production of mCP particles via Drell-Yan, J/Ψ, Υ(1S), Υ(2S), and Υ(3S) channels at 14 TeV center-of-mass energy [2, 3]. Particles produced at the interaction point were propagated using a map of the CMS magnetic field to the proposed experimental site. The effects of multiple scattering and energy loss were included. The number of expected mCP particles per fb^{-1} of integrated luminosity incident at the detector is shown in Figure 2 as a function of the mass of the milli-charged particle. In the second stage, we calculated the signal efficiency by running the kinematic distributions of mCP particles at the proposed experimental site through a full GEANT4 simulation of the detector based on the specifications provided by the manufacturers for Saint-Gobain BC-408 plastic scintillators and Hamamatsu R329-02 PMTs [17, 13]. This was important to model the reflectivity, the light attenuation length and the dependence on small electric charge. Combining the estimated background rates discussed in Section 3 with the cross-sections, acceptances and efficiencies calculated for all masses and electric charges, the sensitivity projections of the milliQan experiment for LHC and HL-LHC are shown in Figure 2.

6 Summary

We have proposed a dedicated experiment to search for milli-charged particles produced in the LHC. This would greatly extend the parameter space for particles with small charge and masses above 0.1 GeV. We have done sufficient R&D to encourage us to proceed with securing funding. We thank T. Camporesi, J. Butler, and the CMS collaboration for their encouragement.

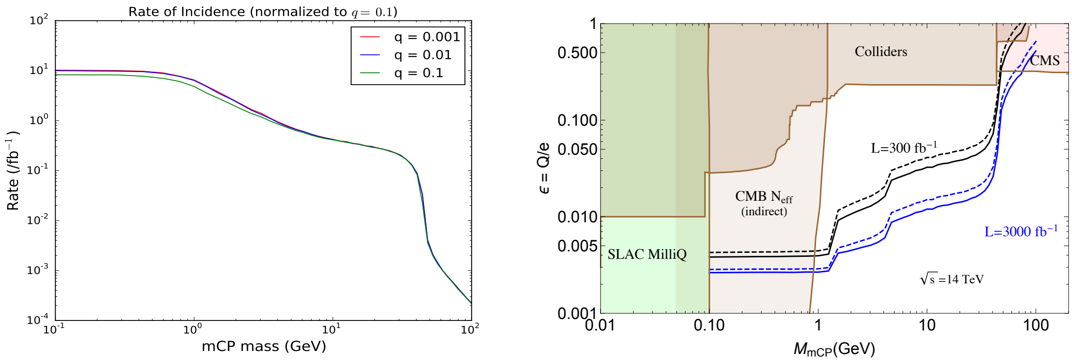

Figure 2: The number of expected mCP particles per fb^{-1} of integrated luminosity incident at the detector, with cross-sections normalized to $Q = 0.1e$ (left). The expected 95% C.L. exclusion (solid lines) and 3σ (dashed lines) sensitivities for benchmark luminosities (right).

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