The MilliQan Experiment and More Searches for Milli-charges

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Particles with Milli-Charges?

Idea -> Hunting for particles with charges ~ 0.3-0.001e
Baseline paper: arXiv:1410.6816
Proposal for a new experiment/CMS subdetector.
Demonstrator (1%) taking data since mid-2017

A Letter of Intent to Install a Milli-charged Particle Detector at LHC P5

Austin Ball,1 Jim Brooke,2 Claudio Campagnari,3 Albert De Roeck,1 Brian Francis,4 Martin Gastal,1 Frank Golf,3 Joel Goldstein,2 Andy Haas,5 Christopher S. Hill,4 Eder Izaguirre,6 Benjamin Kaplan,5 Gabriel Magill,7,6 Bennett Marsh,3 David Miller,8 Theo Prins,1 Harry Shakeshaft,1 David Stuart,3 Max Swiatlowski,8 and Itay Yavin7,6

arXiv:1607.04669

MilliQan Experiment
Proposals for New Experiments @LHC

MilliQan: searches for millicharged particles
MAPP: Same from MoEDAL

CODEX-b: searches for long lived weakly interacting neutral particles

MATHUSLA: searches for long lived weakly interacting neutral particles

FASER: searches for long lived dark photons-like particles

New: AL3X (‘ALICE’ for LLP arXiv.1810.03636)
Milli-Charges

Fractionally charged particles

Posit the existence of a new hidden $U(1)$ with massless field $A'_\mu$:

$$\mathcal{L} = \mathcal{L}_{\text{SM}} + \mathcal{L}_{\text{dark-sector}}$$

$$\mathcal{L}_{\text{dark-sector}} = -\frac{1}{4} A'_\mu A'^{\mu\nu} - \frac{\kappa}{2} A'_\mu B^{\mu\nu} + \frac{1}{2} m_{A'}^2 (A'_\mu)^2$$

$$+ i \bar{\psi} \left( \partial + i e' A' + i M_{\text{mCP}} \right) \psi$$

- $\psi$ is a Dirac particle of mass $M_{\text{mCP}}$, charged under a new $U(1)$ with charge $e'$, and field-strength $A'_{\mu\nu} = \partial_\mu A'_\nu - \partial_\nu A'_\mu$
- $\psi$ is charged under hypercharge with charge $\kappa e'$, a milli-charge
- $\psi$ couples to $\gamma$ and $Z^0$ with $\kappa e' \cos \theta_w$ & $-\kappa e' \sin \theta_w$, respectively.
- Fractional charge is therefore $\epsilon \equiv \kappa e' \cos \theta_w / e$, where $\epsilon << 1$

→ milli-charged particles (mCP) are a natural consequence of extra $U(1)$
Basic Idea for the MilliQan Experiment

- Proposal to add detector that would be sensitive to milli-charged particles produced in LHC collisions

  With $Q$ down to $\sim 10^{-3} e$, $dE/dx$ is $10^{-6}$ MIP -> need long, sensitive, active length to see signal, $\mathcal{O}(1)$ PE.

- Install $\sim 1$ m x 1 m x 3 m scintillator array, pointing back to IP, in well shielded area of Point 5

- With triple coincidence, random background is controlled

Looking for milli-charged particles with a new experiment at the LHC

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We propose a new experiment at the Large Hadron Collider (LHC) that offers a powerful and model-independent probe for milli-charged particles. This experiment could be sensitive to charges in the range $10^{-3} e - 10^{-1} e$ for masses in the range 0.1 – 100 GeV, which is the least constrained part of the parameter space for milli-charged particles. This is a new window of opportunity for exploring physics beyond the Standard Model at the LHC.

Where to put such a Detector

- **Constraints:**
  - *Behind at least 5 m of concrete/rock from the IP*
  - *Space to accommodate the detector (~1m x 1m x 3m)*
  - *Floor loading compatible with detector+support structure (up to 6000 kg)*
  - *Power available, with possibility to add other services*
  - *Selected experimental area should remain clear of “visitors” during data taking*

- **ATLAS did not have an adequate space**

  - MoEDAL experiment (based on our paper) is planning on placing a similar detector at LHC Point 8 (opposite LHCb), **but this location receives only a small fraction of the luminosity delivered by the LHC** But more favorable acceptance..

- With help of CMS physicists in technical roles in early 2016 we identified/selected an appropriate site at LHC Point 5
  - *PX56 observation and drainage “gallery” (aka tunnel)*
Detector Location

100 m underground

CMS cavern

- Sensitivity of experiment $\propto$ length of scintillator
- Sensitivity of experiment $\propto 1/(\text{distance from IP})^2$, 

maximize

minimize

Drainage gallery

$\sim 2.7$ m

$\sim 2.7$ m

17 m of rock shields particles

43.1 deg

17 m
Detector Location

- Sensitivity of experiment $\propto$ length of scintillator
- Sensitivity of experiment $\propto \frac{1}{(\text{distance from IP})^2}$
Detector Concept

- Basic element is a 5 cm² x 80 cm bar of plastic scintillator (BC 408) + PMT (HPK R7725)
- Arranged in a 20 x 20 x 3 array
  - Supported by movable mechanical structure
  - Alignment to IP + retraction to allow passage through gallery
Experimental Set-up

- Basic element is a 5 cm\(^2\) x 80 cm bar of plastic scintillator (BC 408) + PMT (HPK R7725)

- Projective scintillator array requiring multi-layer coincidence and ToF
- Located in tunnel above CMS experiment (33m, \(\phi \sim 43^\circ\), \(\eta \sim 0.7\))
Alignment to CMS

Survey network points installed in drainage gallery

- Survey network points known in CMS coordinate system
  - Support points permanently fixed on walls
  - Accessible and visible from instrument station

- Allows initial alignment good to $< \sim \text{cm}$ (over 33 m!)
- Final alignment using muons from IP
Simulation and Expected Sensitivity

- Use madGraph + madOnia to **simulate production via modified Drell-Yan**
- Propagate particles through parameterized simulation of material interactions with CMS & rock
- Count rate of incidence on 1 m² face of milliQan detector
- **GEANT simulation of milliQan detector** response
- Sensitive to wide range of well-motivated, unexplored, parameter space
  - **$Q/e$ down to nearly 0.0001**
  - **Masses from 100 MeV to 100 GeV**
Expected Backgrounds

- Expect 17 m of rock will shield particles from pp collision (except muons) to negligible levels.

- Muons (from LHC or cosmics) not actually a background since will be very bright (~1M photons in scintillator)
  - *They will be a small source of dead time though*

- Expect irreducible background to be from dark current pulses in PMTs
  - *Assuming dark rate of ~1kHz, triple-incidence in 15 ns window reduces this to ~10^-6 Hz*
    - $O(50)$ bkg events in 3000 fb$^{-1}$

- Expect additional sub-dominant, reducible, backgrounds from activity in the scintillator, background radiation, and photo-multiplier after pulsing.

- Background rate can be monitored *in situ* during beam-off periods.

- Best way to understand backgrounds prior to this is via a concept “demonstrator” detector prototype in drainage gallery
  - *We installed a 1/100 scale such device about 2 years ago*
Experimental Set-up

Detector must simultaneously operate as a very **low background** experiment, while also functioning as a sort of “beam telescope.”

- Shielding from beam particles from LHC
- Long (0.6m – 0.8m) active material: \( \frac{dE}{dx} \propto Q^2 \)
- Multi-layer coincidence in 15 ns to mitigate random tracks

Dominant background: dark current pulses in the PMTs in coincidence with environmental radioactivity and cosmic rays

New design: 3 x 80cm \( \rightarrow \) 4 x 60cm scintillator bars
Demonstrator Design

- In order to verify the feasibility and optimize the design of the experiment thoroughly, ~1% of the detector is installed as a “demonstrator”
- 3 layers of 2x3 scintillator+PMT
Demonstrator Design

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- 3 layers of 2x3 scintillator+PMT
- Scintillator slabs and lead bricks
  - *Tag thru-going particles, shield radiation*
Demonstrator Design

- In order to verify the feasibility and optimize the design of the experiment thoroughly, ~1% of the detector is installed as a “demonstrator”
- 3 layers of 2x3 scintillator+PMT
- Scintillator slabs and lead bricks
  - *Tag thru-going particles, shield radiation*
- Scintillator panels to covering top and sides
  - *Tag/reject cosmic muons*
Demonstrator Design

- In order to verify the feasibility and optimize the design of the experiment thoroughly, ~1% of the detector is installed as a "demonstrator"
- 3 layers of 2x3 scintillator+PMT
- Scintillator slabs and lead bricks
  - Tag thru-going particles, shield radiation
- Scintillator panels to covering top and sides
  - Tag/reject cosmic muons
- Hodoscope packs
  - "Tracks" of beam/cosmic muons
• Supports weight of “final” milliQan
• Rotates out of position to allow passage
Demonstrator Installed in TS2 of 2017

- Upgraded during 2017 YETS

- Been taking data continuously since then (during and between fills)
In the Gallery
In Situ Charge Calibration

- Important because it allows us to study efficiency for small charge depositions
  - Is it sufficient to be able to see milli-charged pls?
  - Want to know number of photoelectrons ($N_{PE}$) that mCP will produce
- Two ingredients:
  - Select cosmic muons from vertical paths
  - Get single photoelectron (SPE) charge from afterpulses
    - (SPE pulse area measurement also done on the bench as a validation)
- With these can calculate $N_{PE}$ for cosmic muon ($Q=1e$)
  - $N_{PE} (Q=1e) = \frac{\text{Pulse area (cosmic muon)}}{\text{Pulse area (SPE)}}$
- Extrapolate this to $N_{PE}$ for fractional charges by $Q^2$

Results are consistent with full Geant4 simulations
Have performed multiple *in situ* measurements important to inform the full detector design and operation.

- Charge calibration using ratio of cosmic muon pulse to single photo-electrons
- Angular resolution and timing using LHC $pp$ muons
- Beam muon occupancy and luminosity dependence
Directly verified milli\(Q\)an capabilities as a charged particle telescope for particles produced in the CMS IP. Next stop, fractionally charged particles!
Collaboration

- ~20 people, 12 institutes, 6 countries
- 9 "CMS" groups
  - The Ohio State University (C. Hill*, B. Francis)
  - University of California, Santa Barbara (D. Stuart, C. Campagnari)
  - The University of Nebraska (F. Golf)
  - CERN (A. Ball, A. De Roeck, M. Gastal)
  - The University of Bristol (J. Brooke, J. Goldstein)
  - Karlsruhe Institute of Technology (R. Ulrich)
  - Lebanese University (H. Zaraket)
  - University of Virginia (C. Neu)
  - FNAL (J. Hirschauer)
- 2 "ATLAS" groups
  - New York University (A. Haas*, B. Kaplan)
  - University of Chicago (D. Miller, M. Swiatkowski)

+VUB, Brussels (S. Lowette)

C. Hill 2018: not quite complete person list
More Milli-Charge Hunting

A proposal for milli-charges at FNAL @ MINOS near detector

See also: arXiv:1806.03310

Based on the MilliQan design

See also MoEDAL talk for another proposal
More Milli-charge Activities

Physics Beyond Collider Study

arXiv:1901.09966

Physics Beyond Colliders at CERN
Beyond the Standard Model Working Group Report

Millicharged Particles in Liquid Argon Neutrino Experiments

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arXiv:1902.03246

LArTPC study
Status of the Various Projects

Based on Simon Knapen
FNAL seminar fall 2018 (*)

### Lifetime frontier

#### Supplementary detectors

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- FASER1/MilliQan(?) installation by 2021
- MATHUSLA, CODEX-b, FASER2 for HL-LHC

(*) Experiments have different capabilities for measuring the LLPs
MilliQan aims to search for milli-charges in the regime $0.1 < Q < 0.003$

MilliQan demonstrator installed in mid-2017 and taking data since (1% of a full module). First physics with the demonstrator results?

Funding requests under evaluation (NSF-MRI, European requests). Expect outcome soon.

Detector ready to be constructed, as soon as funding becomes available, for run-III

More initiatives for milli-charge searches, at CERN and FNAL in progress