A proposed milli-charged particle detector at LHC Point 5

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(which we call \textit{milliQan})
Summer 2014 … ready for Run 2 of LHC?

- At a workshop at ICTP in Trieste, I was asked to give a talk on this topic meant to stimulate discussion on whether there were any important uncovered areas in the planned LHC physics program
  - *For the main goal for Run 2 of searching for a natural solution to Hierarchy problem, the conclusion was basically yes*
  - **Over the course of Run 1, we did a good job of plugging most/all holes already, or at least would do so with the data from Run 2**

- BUT, at around this time the ideas of neutral naturalness were emerging
  - *Natural solutions to HP, where BSM states are not charged under SM so evade LHC detection*
  - Likewise for DM program, depending on nature of DM might not couple directly to protons and could evade LHC detection
  - One can generalize these scenarios as those where BSM states are in hidden/dark sector only accessible through some portal

### One organizing principle for probing it: focus on lowest-dimension allowed interactions:
- vector portal, Higgs portal, neutrino portal

\[
\langle Y, B^{\mu
u}B^{'\mu\nu} \rangle \quad \langle h|h|^{2} \phi \rangle^{2} \quad \langle \nu,Lh\psi \rangle
\]

- Run 2 program covers Higgs portal (and neutrino portal not directly accessible), but what about vector portal?
  - Massive dark photons (~covered)
  - **Massless dark photons, not covered**
But massless dark photons have a distinctive signature, “millicharged” particles!

- If you add a new U(1), get mixing with SM U(1)
  - Generically, charge carriers of new U(1) will have small EM charge, proportional to the mixing
  - Holdom PLB 196-198 (1986)
  - Typically $10^{-2}$ to $10^{-3}$ e, so they are called “millicharged particles”

- Due to small EM charge interact very weekly with typical, ionization based, particle detectors
  - Need dedicated experiment to search for these

\[
B_{\mu\nu} \sim B'_{\mu\nu} \quad \mathcal{L} = \mathcal{L}_{SM} - \frac{1}{4} B'_{\mu\nu} B'_{\mu\nu} - \frac{\kappa}{2} B_{\mu\nu} B'_{\mu\nu}
\]

If there are new fermions charged under the new U'(1)

\[
\mathcal{L} = \mathcal{L}_{SM} - \frac{1}{4} B'_{\mu\nu} B'_{\mu\nu} - \frac{\kappa}{2} B'_{\mu\nu} B_{\mu\nu} + i \bar{\psi} (\dot{\phi} + ig_D B' + i M_{mCP}) \psi
\]

\[
B'_{\mu} \to B'_{\mu} + \kappa B_{\mu}
\]

Gets rid of “mixing term” and generates an apparent milli-hypercharge for the new fermions

After electro-weak symmetry breaking DS fermions acquire an EM charge

\[
Q = \kappa g_D \cos \theta_W
\]

(normalized to charge of electron)
Basic Idea for 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 large, sensitive, active area 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

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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 could we put such a detector?

- **Constraints:**
  - Behind at least 5m 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 does not have an adequate space**

- MoEDAL experiment (based on our paper) is thinking of 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**

- 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)
The PX56 Observation and Drainage gallery

- The PX56 drainage gallery was used during the excavation phase of the CMS experimental area.
- It links the 2 CMS shafts PM54 and PX56 together.
The gallery has a basic shotcrete finish. Dimensions are 2.78 m in height, 2.73 m in width. Basic power, lighting, drainage available. Only existing use is for infrequent transit to PX56 platform (interlocked during LHC operation).
Where should we put it in drainage gallery?

- Sensitivity of experiment $\propto$ length of scintillator
  - *want to maximize what can fit in dimensions*

- Sensitivity of experiment $\propto \frac{1}{(\text{distance from IP})^2}$,
  - *want to minimize this distance, while satisfying above*

- Optimized location found:
  - 33 m from IP
  - 17 m through rock
  - Angle from horizontal plane is 43.1 deg

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In 2015, Theo P carried out siting studies to identify the best location for MilliQan.

In 2016, Harry S further defined the foreseen position of the detector.

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17/02/17
Alignment to CMS IP

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 < ~cm (over 33 m!)
- Final alignment using muons from IP

How we perform the alignment afterwards...

1. Measurement of survey network points installed in the drainage gallery and known in CMS coordinate system
2. Measurement of outer survey reference points on MilliQan detector to determine them in CMS coordinate system
3. Calculation of detector center and orientation wrt CMS coordinate system (based on fiducialisation)
4. Calculation of correction values for detector alignment
5. Then MilliQan team needs to correct the detector position by the given values
6. Control of detector position by survey
7. Further correction of detector position by MilliQan team if necessary (for each position correction, we repeat points 2 to 6)

The alignment of the detector depends on the quality of the adjustment possibilities! Each iteration takes time! Without mechanical fine-tuning it will take a lot of iterations and you will not reach the nominal position!
Overview of Proposed Detector

- Basic element is a 5 cm$^2$ 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
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*
    - \( \mathcal{O}(50) \) bkg events in 3000 fb\(^{-1} \)

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

- Actual background rate will ultimately be measured *in situ* during beam-off periods
  - *Can also measure backgrounds from non-pointing coincidence during beam on periods.*
Simulation & 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 m$^2$ 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 0.001
  - Masses from 100 MeV to 100 GeV

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**FIG. 4**: Depiction of the (a) full detector and (b) a single scintillating block with coupled phototube, as implemented in the Geant4 detector simulation. The mCP is yellow and radiated photons are green.

**FIG. 6**: Expected sensitivity for different LHC luminosity scenarios. The black line shows the expected 95% C.L. exclusion (solid) and 3σ sensitivity (dashed), assuming 300 fb$^{-1}$ of integrated luminosity. In blue we show the corresponding expectations for 3000 fb$^{-1}$.

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Timeline & Next Steps

- Have experiment ready for physics before Run 3 (2020)
  - Construction/Installation during LS2
  - Take data for Run 3, 4, 5, …
- Install 1/100 detector prototype to get first data before end of Run 2 (2018)
  - Install, commission during TS2, YETS later this year (2017)
  - Will be only opportunity to make in situ background measurements when beam is present before Run 3
  - Allows us to react (e.g. add’l shielding) during construction in LS2
- Have written LOI, in discussion with CMS to work out collaborating details
  - I won’t talk about this, so don’t ask :-)
- Can fund prototype run, seeking construction funding now

12 full scintillators + PMTs will be installed during TS2

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,9 and Itay Yavin7,6

1 CERN
2 University of Bristol
3 University of California, Santa Barbara
4 The Ohio State University
5 New York University
6 Perimeter Institute for Theoretical Physics
7 McMaster University
8 University of Chicago
9 Dated: July 19, 2016
Prototype coming together ….

- Support structure constructed on surface at CERN in June
- Lowered into CMS cavern during TS1
- Installed through cavern door into drainage gallery
- Prototype milliQan on track to be installed in TS2
  - Construction completed at UCSB in July
  - Shipped to NYU for integration in August
  - Transport to CERN by September
Summary

• **milliQan** is a proposed dedicated experiment that would detect **millicharged particles** produced by pp collisions at **LHC point 5**

• The experiment would be **installed during LS2 in a vestigial drainage gallery above CMS**

• Our initial calculations+simulations indicate that 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.

  • *R&D indicates actually sensitivity could be significantly better than this*
  
  • *In reality will only know after in situ experience, which we will get with a 1/100th scale prototype which will be installed in September*

• In any case, full-scale milliQan, scheduled for Run 3, will **greatly extend the parameter space explored for particles with small charge and masses above 100 MeV.**
Additional Material
Basics of Readout & Trigger

• Readout via CAEN V1743 12 bit digitizer
  • 16 channels
    • Sampled at 3.2 GS/s (a sample each 312.5 ps)
    • 1024 analog buffer ring (320 ns long).
    • Analog noise is about 0.75 mV per channel, allowing good identification of and triggering on single PE signals

• Trigger
  • If 2 of 3 bars coincident in 15 ns window, self-triggers to read out whole detector
    • Separate from CMS trigger
  • Data will be read out via CAEN CONET 2 over 80 Mbps optical fiber to a PCI card in dedicated DAQ
    • Separate from CMS DAQ
Design of Support Structure

• M. Gastal, R. Loos (CERN) working with engineers from Lebanese University on support structure
  • Splitting in 2 gives much more clearance
Powering, Slow Controls, Monitoring, Timing

- Operationally, milliQan will be independent from CMS
  - Self-triggering, separate dedicated DAQ, separate dedicated DCS
- Only needs from CMS would be basic infrastructure (power, ethernet), delivered luminosity, and LHC clock
  - Few other things would be nice (e.g. Run / luminosity section / orbit markers, BPTX)

Timing box receives TCDS fibre from CMS
- Recover LHC clock and send to V1743
- Decode CMS run/lumi/orbit signals
- Receive trigger from V1743, and readout data to PC
Cooling PMTs will improve sensitivity

- While cooling PMTs will complicate infrastructure/safety requirements, modest cooling can provide almost an order of magnitude reduction in dark rate
  - Sensitivity estimates used 550 Hz per PMT
  - Ongoing R&D into cooling
    - 80 Hz per PMT with cooling to -20 deg C

![Graph showing dark rate vs temperature](image)

*Using our "cooler", can test dark rate vs PMT temperature*

*Using ethanol, we can easily go down to -30C, and probably push lower*

*For old tubes, like our Hamamatsu R329-02 or R2083, we saw some decrease in rate when cooling, but the 9814B is dramatic and repeatable*

![Diagram of possible cooling concept](image)

*Detector cooling concept*

*02/06/17*

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Current composition of milliQan

- ~20 people, 12 institutes, 6 countries
- 8 “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)
  - Indian Institute of Science (J. Komaragiri)
  - Karlsruhe Institute of Technology (R. Ulrich)
  - Lebanese University (H. Zaraket)
- 2 “ATLAS” groups
  - New York University (A. Haas*, B. Kaplan)
  - University of Chicago (D. Miller, M. Swiatlowski)
- 2 “Theory” groups
  - Perimeter Institute (I. Yavin G. Magill)
  - Brookhaven National Lab (E. Izaguirre)

*denotes co-spokepersons