Status of the milliQan Experiment

Christopher S. Hill
The Ohio State University
on behalf of the milliQan collaboration
What is milliQan?

Complementary LHC hidden/dark sector search — massless dark photons not covered by ATLAS/CMS searches, but have distinctive signature:

Consider an additional U’(1) mixing with SM U(1):

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

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

New fermions charged under this U’(1) will have a fractional EM charge (after EWSB) — Holdom PLB 196-198 (1986):

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

For interesting range, Q~10^{-2} – 10^{-3} e can discover such “millicharged” particles with a dedicated experiment at the LHC
Idea for milliQan ~2014

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.

• Add detector sensitive to milli-charged particles produced in LHC collisions
  • *With Q down to ~$10^{-3}e$, dE/dx is $10^{-6}$ MIP -> need long, sensitive, active length to see signal, 6(1) PE.*

• Install ~1 m x 1 m x 3 m scintillator + PMT array, pointing back to IP, in well shielded area near CMS/ATLAS

• With triple coincidence, expectedly dominant random background should be controlled

Proposed location

2.78m high, 2.73m wide
33m, $\phi \sim 43^\circ$, $\eta \sim 0.7$ from CMS IP
17m rock shielding

September 2017: install “demonstrator” to study backgrounds and optimize design
1/100th scale Demonstrator

- Three layers of 2x3 scintillator + PMT
  - 1% of full milliQan
  - Saint-Gobain BC-408 plastic scintillator, 2”x2”x80cm
  - Several PMT species: HPK R7725 / R878, ET 9814SB
1/100\textsuperscript{th} scale Demonstrator

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  - Track beam/cosmic muons
  - SiPM readout with FPGA/Raspberry Pi
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  - SiPM readout with FPGA/Raspberry Pi
- Dual CAEN V1743 digitizer readout
  - 31 + (1 LHC clock phase) analog channels
  - Up to 3.2 GS/s — run at 1.6 GS/s (640 ns/acq.)
Status of Demonstrator

- Fall 2017: installed 2x2x3 prototype
  - **Structural mount designed to hold full detector**
- April 2018: To aid understanding of backgrounds, upgraded to 2x3x3, added veto panels and slabs & second digitizer
- Very successful 2018 run: ~37/fb, >2000h trigger live-time
  - **Valuable experience in operating detector**
- December 2018: installed 2 additional channels in a fourth layer as design option
- Powerful resource to study/optimize performance of final detector
Highlights from Demonstrator Data

- “see” muons from CMS IP
  - Validated GEANT efficiency
- *in situ* N_{PE}/Q calibration from cosmics
  - Further validated simulation
- Established ABCD method to estimate backgrounds
  - Observed correlated backgrounds
  - Changed to 4-layer design
- Reduced background by ~2 orders magnitude compared to 3-layers

Event display of a muon from CMS

3 Layer v. 4 Layer Closure Test

<table>
<thead>
<tr>
<th>N_{PE}</th>
<th>Events/hr</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>10^{-1}</td>
</tr>
<tr>
<td>2</td>
<td>10^{-2}</td>
</tr>
<tr>
<td>3</td>
<td>10^{-3}</td>
</tr>
<tr>
<td>4</td>
<td>10^{-4}</td>
</tr>
</tbody>
</table>

Measured rate — 0.19/pb$^{-1}$
Rate from simulation — 0.22/pb$^{-1}$
Engineering Completed for Full Scale Detector

- Have FEA tested final designs for
  - modules & services
  - support “cage”
  - Insertion and alignment hardware
milliQan Sensitivity to Dark Sector

- milliQan sensitivity estimated via
  - madGraph + madOnia + GEANT full simulation
  - in situ measured background rates
- Discovery potential for
  - Q/e down to nearly 0.001
  - Masses from 100 MeV —100 GeV

Studied as part of Physics Beyond Colliders (PBC) group at CERN

- CERN-PBC-REPORT-2018-003
- Complementary reach to all other proposed dark sector experiments
Timeline & Next Steps

- Seeking funding to build complete detector (next attempt will be NSF MRI)

Demonstrator installed, upgraded

Publish demonstrator results

Build full detector, begin data-taking only if we get $$

upgrade for HL LHC?
Summary

- **milliQan** is a proposed experiment sensitive to millicharged particles (mCPs) produced by LHC
  - Complementary approach to probe dark sector
    - mCPs arise when dark mediator is ~massless (as some hints from astrophysics suggest)
    - Sensitive to unexplored 100 MeV — 100 GeV and Q<0.3e region
  - 1% demonstrator been taking data for ~2 years
    - Validated design & measured backgrounds
    - Experience in constructing, operating detector, data analysis
      - Plan to publish first results while waiting for full funding
  - Full milliQan design is already quite advanced

**We are ready for construction!**

*However, funding efforts to date have not been successful* (despite well-reviewed proposals)

MilliQan will be an interesting and relatively cheap extension of the LHC physics program — if it’s built!

Up to us (milliQan + LHC community) to make case that $ is needed NOW for small experiments like this
Additional Material
Simulation & Expected Sensitivity (LOI)

• 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 0.001*
  
  - *Masses from 100 MeV to 100 GeV*
**In situ Charge Calibration**

\[ Q = 1 \rightarrow \text{many scintillation photons} \]

\[ Q \ll 1 \rightarrow \text{few/single photon(s)} \]

- For a given Q, need to know the number of photo-electrons \( N_{PE} \) produced
- Calculate \( N_{PE} \) produced by a cosmic muon \( (Q = 1\text{e}) \), and scale response by \( Q^2 \)
- Find the pulse area for a single photo-electron (SPE):

\[
N_{PE} = \frac{\text{pulse area (cosmic)}}{\text{pulse area (SPE)}}
\]
Demonstrator: *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 $Q^2$
Demonstrator Results: *in situ* charge calibration

Pulse area as a function of HV for a PMT

- $N_{PE}$ for $Q=1e$ is $\sim 5k$
- Flight distance of cosmic muons in scintillator is 5 cm
- For through-going muons, the flight distance is 80 cm
- $N_{PE}$ for thru-going muon is $5k \times \frac{80}{5} = 80k$
- Since $N_{PE}$ is proportional to $Q^2$
  - $N_{PE} = 1$ for $Q \sim 0.003e$
- Consistent with full Geant4 simulation results (and calculations in original paper)
Demonstrator: *muons from CMS*

- Use the demonstrator to study muons from pp collisions in CMS
  - *Select thru-going particles*
  - *Useful for alignment, triggering, timing calibration, etc*

Event display of a muon from CMS

CMS instantaneous luminosity

Number of thru-going particles
Demonstrator Results: *muons from CMS*

- Demonstrator is “seeing” muons from collisions at CMS IP
- Reproduces both integrated and instantaneous luminosity recorded by CMS

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**milliQan CMS luminosity**

- **time constant** = 13 ± 2 h
- **beam lifetime** = 14 h
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
Powering, Slow Controls, Monitoring

- 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
Alignment to CMS IP (without line-of-sight)

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)

CMS coordinate system

Detector coordinate system

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!
Demonstrator Upgraded during 2017-18
YETS

- Now have 18 milliQan bars
- 9 thin scintillator veto sheets
- 4 scintillator slabs between bars
- Expanded hodoscope
- Timing information from CMS
- 4 magnetic field sensors
- Temperature & humidity sensors
- Fire protection system

Channel Map
Post-YETS 18

Timing Card
0.15

Particles

R878
ET
R7725

N.B.: 0.11 and 1.14 switched, correct as shown
Interaction (dark photon) can mix with the photon in the Standard Model, resulting in milli-charged particles. To explain the existence of dark matter, a dark photon in the dark sector is introduced. A photon in the dark sector produces light when charged and would be in the GeV range unprobed, produced at the LHC and would be ready to improve understanding backgrounds.

**FIG. 7:** Expected sensitivity for di-sector is introduced. A photon in the dark sector is expected to improve sensitivity. The next step in the milliQan project is to seek external funding to enable at least the following timeline:

- **Construction + Installation of remainder of detector during LS2 (2019–2020)**
- **Commission and take data in order to evaluate beam-on backgrounds**
- **Installation of demonstrator in PX56 by end of Run 2 (YETS 2017 + TS in 2018)**
- **Construct small fraction of detector**
- **Location of detector in tunnel above LHC collision point**
- **Operate detector for physics for duration of Run 3 and HL-LHC (mid 2021–)**
- **Final commissioning by spring 2021**

**Detector Concept:**

- **Detector unit:** 5x5x80 cm scintillator + photomultiplier
- **Mechanics:**
  - **Slab1:** 2x3
  - **Slab2:** 2x3
  - **Slab3:** 2x3
- **Conversion:**
  - **Slab4:** (top, not shown in the photo) needs a mount that packs and bars: putting some tape would be enough
  - **No support for slab1 because it fits nicely between HS**
  - **L-Shape support for slab2 and 3 made by Rob**
  - **Added one vertical pack to top HS**
  - **Added one horizontal pack to bottom HS**
  - **Moved sidecar bars to the top right side of each layer**
  - **Added new bars to the top left side of each layer**
  - **Moved sidecar bars to the top right side of each layer**
  - **2x2 configuration not touched except for the ch8 and ch9 bar and ch8 bar and ch9 bar switched**
  - **R7725 on ch8 replaced with R878**
- **Rate [hour⁻¹]:**
  - **0**
  - **100**
  - **200**
  - **300**
  - **400**
  - **500**
  - **600**
- **Middle and top layers: UCSB bar + PMTs**
- **Bottom layer: OSU bars**

**Installation team in front of the demonstrator:**

- **Brian Francis (OSU)**
- **Ryan Heller (UCSB)**
- **Josh De La Haye (CERN)**
- **Jae Hyeok Yoo (UCSB)**
- **Max Swiatkowski (U. Chicago)**
- **Matthew Citron (UCSB)**
Demonstrator Upgraded during 2017-18

YETS

- Added additional set of milliQan bars in vertical dimension to aid with cosmic identification
- Added thin sheets on scintillator on top and side to aid in cosmic veto
- Added scintillator slabs between between bars to help understand longitudinal “showers”
- Added some environmental sensors to help understand environment
- Added more hodoscope packs to aid in “tracking”
Demonstrator: timing of thru-going particles

E.g., muons from collisions

Event display of a muon from CMS

Distance between top and bottom = 3.6 m

Top hit time - bottom hit time [ns]
Alignment of demonstrator

- The detector had to be aligned with CMS IP
  - Projection of CMS network into gallery done during TS1
  - Alignment of detector carried out by Noemie Beni and Benoit Cumer
Charge calibration: bench setup

LED: Thorlabs LED430L
430 nm (blue/violet)

PMTs:
Hamamatsu R878
Hamamatsu R7725

3D-printed casing to hold PMT, LED, filters

Can control \( N_{PE} \) by varying amplitude of input LED pulse

Trigger scope on the LED pulse, so PMT response falls in well-defined time window

No need for any peak-finding, and allows us to trigger on “blank” (0-PE) events

PMT:
Hamamatsu R878
Hamamatsu R7725

Optional cardboard light-blocker

2000x filter

20 ns pulse

Function Generator

20 ns pulse

DRS (scope)

PMT Output

PMT

HV

e.g. -1450 V

LED

32
Charge calibration: bench results

R878 @ 1450V

1PE peak at 80 pVs

LED On @ 2.9 V
LED Blocked @ 2.9 V

\[ \langle N_{PE} \rangle = 1.71 \]

\[ E(\text{SPE}) = 69.9 \text{ pVs} \]

\[ \sigma(\text{SPE}) = 32.0 \text{ pVs} \]
## Status on Searches for Mini-charged Particles (mCPs)

A long history of direct and indirect searches for mCPs

For mCPs with mass below $m_e$ one finds strong bounds from astrophysics and cosmology

<table>
<thead>
<tr>
<th>Astrophysics</th>
<th>Cooling and energy loss bounds from stars and SN</th>
</tr>
</thead>
<tbody>
<tr>
<td>Cosmology</td>
<td>BBN and CMB number of effective relativistic degree of freedom bounds</td>
</tr>
<tr>
<td>Laboratory</td>
<td>Direct bound from the invisible decay of ortho-positronium</td>
</tr>
<tr>
<td>Direct bound from the Lamb shift</td>
<td>Direct constraint from accelerators: SLAC Milli-Charge experiment, E613, ASP, LEP</td>
</tr>
</tbody>
</table>
SLAC MilliCharge Experiment

29.5 GeV pulsed electron beam

~ \(10^{19}\) electrons on target

Good time resolution is essential, and tricky for small (SPE) pulses!

mQ detector
2x2 blocks of 21 cm x 21 cm x 130 cm plastic scintillator

Predicted Shape of mQ-induced Peak in the Time Spectrum, Assuming SPE-size Events
This flattening is artificial, as we did not include the more complicated production of mCP from QCD/hadronic physics ... (only DY and prompt resonances).
Additional Physics Motivations

More Motivation?

- Recent excitement that milli-charged dark matter at the 1% mass-density level is a leading explanation for the EDGES 21-cm result

- The mass/charge region favored is in a sweet-spot of milliQan sensitivity

- Also other signals beyond mCP... like heavy neutrinos with large eDM:

  arXiv:1803.03091
  arXiv:1710.06894
1. **Millicharged + cold dark matter** can consistently produce striking 21-cm signatures, and can explain the EDGES observation.

2. **Broad range of parameter space** allowed: \( \text{GeV} \lesssim m_m \lesssim \text{TeV} \) with \( f_m \lesssim 0.4 \% \), and \( m_C \lesssim 10 \text{ GeV} \).

3. Very testable at **beam experiments** and **direct detection**, both current and future.