milliQan: search for milli-charged particles at the LHC

Matthew Citron
No sign of new physics at the LHC

LHC ring

What could we be missing? Look to dark matter - many SM extensions include a **dark or hidden sector**
Why milli-charged?

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

massless U'(1) boson in the dark sector

‘dark EM’

\[ \kappa \sim 10^{-3} - 10^{-2} \]
(naturally \( \sim \alpha/\pi \))

Kinetic mixing with a new massless ‘dark’ boson can provide link between SM and a hidden/dark sector
Why milli-charged?

Now add fermion charged under new U'(1):

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

Standard trick - redefine gauge field B': \[ B' \rightarrow B' + \kappa B \]

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

new fermion has small EM charge: **milli-charged particle**
Many ways to search for mCP

\[ Q = \epsilon e \]

Searches using colliders, effects on sun, stars and supernovae, cosmological bounds,\ldots cover wide range in masses/charges

**but**

big gap for heavier (\(\sim\) GeV) low charged particles \(\rightarrow\) requires dedicated experiment

target with **milliQan** at the LHC!
milliQan detector concept

Initial design in 2016 LOI: 1200 scintillating bars in three layers (400 pointing paths)

**Key idea**: use scintillator bar array to detect (very) small ionisation from low charged particles produced by the LHC

- Expected signal: few scintillation photons in all three layers
- Each bar + PMT must be capable of detecting a single scintillation photon
- Control backgrounds: signal in each layer within small time window and which points towards the IP
- Easy to scale and adapt!

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Proposed location

- Place detector in CMS experimental site within existing ‘drainage gallery’
- Location 33 m from interaction point (including 17 m rock) → beam particles greatly suppressed
Proposed location

2.78m high
2.73m wide

Sept 2017: milliQan demonstrator installed to study backgrounds and prove feasibility of the experiment!
Demonstrator components

- 3 layers of 2x3 scintillator+PMT
  - ~ 1% prototype of full milliQan detector

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- Scintillator slabs and lead bricks
  - Tag thru-going particles, shield radiation

scintillator slab
lead brick
Demonstrator components

- 3 layers of 2x3 scintillator+PMT
  - ~ 1% prototype of full milliQan detector
- Scintillator slabs and lead bricks
  - Tag thru-going particles, shield radiation
- Scintillator panels to cover top + sides
  - Tag cosmic muons
Demonstrator components

- 3 layers of 2x3 scintillator+PMT
  - ~1% prototype of full milliQan detector
- Scintillator slabs and lead bricks
  - Tag thru-going particles, shield radiation
- Scintillator panels to cover top + sides
  - Tag
- Hodoscope packs
  - Track beam/cosmic muons
- Environmental sensors to measure humidity and magnetic field
Demonstrator

• Ran very successfully, collecting \(\sim 35/fb\), 2000h of data in 2018

• Operational experience in difficult environment: triggering/DAQ/DQM

• Used for range of studies to prove feasibility of full detector

• Key results on next slides: alignment, calibrations, background measurements

• Fully simulated in GEANT4

Installed on mount designed to hold full detector
Alignment

- milliQan ‘sees’ muons from the CMS interaction point

- Check occupancy agreement with expectation
  - Simulate production at CMS interaction point
  - Propagate through CMS material and 17 m of rock considering **multiple scattering** and CMS magnetic field

- Expected rate: $0.28 \pm 0.09 / \text{pb}^{-1}$
- Measured rate: $0.19 / \text{pb}^{-1}$
Calibrations

- **In-situ charge calibration**
  - Calculate $N_{PE}$ produced by a cosmic muon ($Q=1e$) per PMT and scale ($Q^2$)
  - Find $N_{PE} = 1$ for $Q \sim 0.003e$ → consistent with result from full GEANT4 simulation

- **Timing calibration**
  - Cable length, PMT rise time and geometric differences must be calibrated
  - Achieve $\sim 4$ ns resolution → easily sufficient for 15 ns window between hits in layers (as assumed in LOI)

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Background measurement

- Detector **aligned** and **calibrated** - measure backgrounds for full milliQan detector

- Major lesson from demonstrator: dark rate subdominant background source

- Motivates update to ‘four layer’ design → achieve targeted background rate

### Background measurement

**Two-fold coincidence**

**Three-fold coincidence**

**Four-fold coincidence**

- Observed average rate per path
- Predicted dark-current rate from demonstrator data
- Using assumptions in Refs. [1, 2]

*Signal selection: coincident hits within 15 ns (pointing to IP)*
Signal simulation

- Wide range of production mechanisms considered!
- Propagate to detector with response **fully simulated** in GEANT4
- Expect **new sensitivity** already using demonstrator data (search design/backgrounds in backup)

**σ × B / Q² [pb]**

- Total $\zeta^{+}\zeta^{-}$ cross section ($\pm 1 \sigma_{theory}$)
- $\pi^{0} \rightarrow \zeta^{+}\zeta^{-}$
- $\rho \rightarrow \zeta^{+}\zeta^{-}$
- $J/\psi \rightarrow \zeta^{+}\zeta^{-}$
- $\Upsilon(1S) \rightarrow \zeta^{+}\zeta^{-}$
- $\Upsilon(2S) \rightarrow \zeta^{+}\zeta^{-}$
- $\Upsilon(1S) \rightarrow \zeta^{+}\zeta^{-}$
- $\Upsilon(2S) \rightarrow \zeta^{+}\zeta^{-}$
- $\Upsilon(3S) \rightarrow \zeta^{+}\zeta^{-}$
- $\rho \rightarrow \zeta^{+}\zeta^{-}$
- $J/\psi X \rightarrow \zeta^{+}\zeta^{-}$
- $\phi \rightarrow \zeta^{+}\zeta^{-}$
- $\eta \rightarrow \zeta^{+}\zeta^{-}$
- $\psi(2S) \rightarrow \zeta^{+}\zeta^{-}$
- $\psi(3S) \rightarrow \zeta^{+}\zeta^{-}$
- $\psi(2S) \rightarrow \zeta^{+}\zeta^{-}$
- $\psi(3S) \rightarrow \zeta^{+}\zeta^{-}$
- $B \rightarrow \eta \zeta^{+}\zeta^{-}$
- $B \rightarrow \psi \zeta^{+}\zeta^{-}$
- $Drell-Yan^*$

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Mechanical structure for full detector

- Plans for mechanical structure finalised with **four layers**

- Constraints: maximum bars in minimal space: two adjacent detectors of 9x6x4x4 = 864 bars (1 x 1 x 3 m)

- Use mounts as in place in drainage gallery

**Composition of a detector module**

- Side
- 4x4 scintillator unit group
- Lead block
- Support
Full detector expected sensitivity

First detector sensitive to ~mCP at GeV ranges!

NB - this bound assumes a massless dark photon

from 2016 LOI - update coming (very) soon!

flattening artificial:
no mCP production from QCD/hadronic processes included (only DY/prompt resonances)!
Timeline/next steps

Demonstrator installed

Build full detector and start taking data: only if we get $$

Publish demonstrator results

upgrade for HL LHC?
Conclusions

- The milliQan detector can provide **unique sensitivity** to milli-charged particles

- Built, commissioned and operated small prototype to **prove feasibility** and **measure background** rate for full detector
  - Plan publication using data collected in 2018 with new sensitivity!

- Signal generation, propagation and detector response **fully simulated**

- **Full mechanical** design for detector finalised

- We are ready for construction but …
  - No funding secured so far despite (well reviewed) proposals to various agencies/foundations
  - Without funding soon, the opportunity to carry out this interesting (and relatively cheap) extension of the LHC physics program will be in jeopardy
milliQan collaboration

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Backup
PMTs

High gain and fast (but expensive)

Hamamatsu R7725

Electron Tube 9814B

Older/slower but free (taken from older experiment)

Hamamatsu R878

Demonstrator used to find strengths/weaknesses of various PMT species
Module assembly

Bars wrapped in layers of reflective and light blocking materials (including tyvek, tinfoil, electrical tape)

3D printed PMT casing

Fibre glass mounts for each layer
Going underground (via the CMS shaft)

Modules assembled on the surface and then lowered to gallery
Mount aligned to CMS IP with 1cm³ accuracy

Designed to hold full milliQan
Backgrounds

- Beam backgrounds rejected by rock
  - Leaves ~15 muons/minute which reach detector

- Cosmic muons
  - Through-going rate few/minute (~1% rate at surface)

- Showers of n/γ/e from beam/cosmic muons in rock/detector material

- Random overlap of dark pulses within PMTs

- Radiation within PMTs and cavern walls

Muons clearly distinguishable from signal

Reject with multi-layer coincidence and active veto requirements
In-situ charge calibration

- Need to know number of photons ($N_{PE}$) produced for a given $Q$
- Calculate $N_{PE}$ produced by a cosmic muon ($Q=1e$) and scale ($Q^2$)
- $N_{PE}(Q=1e) = \text{pulse area (cosmic)/pulse area single photon (SPE)}$
- Find $N_{PE} = 1$ for $Q \sim 0.003e \rightarrow$ consistent with result from full GEANT4 simulation

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

$p = \text{pulse}$

Carlos Hernandez Faham
Thru-going particle timing

- Reject random dark rate background using small time window between hits in layer
  - Cable length, PMT rise time and geometric differences must be calibrated
- Resolution ~4ns - easily sufficient for triple coincidence in time window at least as small as assumed in LOI (15ns)!

\[ \Delta T \approx \frac{2 \times 2.2}{c} = 15\text{ns} \]
SPE calibration using LED

Will show results for example PMT (R878)
SPE calibration using LED

First find average NPE from LED

Use ‘LED blocked’ dataset to measure 0 PE template

Scale to match left edge of LED unblocked (area < 0)

Input N_{PE} from LED is poisson distributed:

\[ \langle N_{PE} \rangle = -\log(\text{events}_{N=0}/\text{events}) \]

for this LED (at this voltage) find \( \langle N_{PE} \rangle = 1.71 \)

SPE calibration using LED

Now calculate SPE area

Only assume linear PMT response (true for low NPE)

\[ <A_{SPE}> = \frac{<A_{LED \, on}> - <A_{pedestal}>}{<N_{PE}>} \]

Similar trick to find \( \sigma \)

no functional form assumed for area of SPE or pedestal!

For this PMT (at 1450V):

\[ <A_{SPE}> = 69.9 \, \text{pVs} \]
\[ \sigma = 32 \, \text{pVs} \]

SPE calibration in-situ

- Calibration using LED ‘gold standard’ but can’t use this method in-situ
  - Have carried out for both an R7725 and R878 PMT

- Need method to approximate SPE area during data taking
  - In case of drift, effect of magnetic field (see later), etc…

- Calibrate using delayed scintillation pulses
  - Caveats: contamination from ion afterpulses, potential bias from pulse identification, no accounting for ‘partial’ SPEs
Calibration from delayed scintillation pulses

Run 700, File 3, Event 4655 (beam off)

Initial pulse from e.g. radiation

afterpulses (delayed scintillation photons)

Build up pulse area distribution from ‘cleaned afterpulses’ (no pulse in preceding 20ns)

e.g. R878 PMT

Mean within half-width-max gives SPE pulse area
Calibration from delayed scintillation pulses

Run 716, File 6, Event 1257 (beam off)

Initial pulse from e.g. radiation
afterpulses

Build up pulse area distribution from ‘cleaned afterpulses’
(no pulse in preceding 20ns)

e.g. ET9814B PMT

Mean within half-width-max gives SPE pulse area
Effect of magnetic field

- Drainage gallery has residual magnetic field from CMS
- Measure field both inside and outside of PMT shielding (mu-metal)
- Look at effect on PMTs
Effect of magnetic field
e.g. R878

- B field can have large effect on NPE as primary electrons can be deflected
- Shows importance of in-situ calibration
- Size of effect varies between species and orientation of PMTs in field
  - Important consideration for full detector (ETs/878s work well!)

B field

In B field can lose electrons!
Designing a search

- Detector **aligned and calibrated** - now define search regions and measure backgrounds for demonstrator

- Signal selections:
  - Single channel hit per layer
  - Pointing path in three layers
  - No activity in rest of detector
  - Max time window between layers < 15ns

- Two methods to measure backgrounds: beam-off periods and ‘ABCD’
Background measurement

- Measurement with data collected during beam-off periods consistent with ‘ABCD’ prediction using beam-on data

- Beam component to background subdominant (confirming in simulation now)

\[
N_A \text{ (signal)} = N_B \times \frac{N_C}{N_D} \text{ (per NPE bin)}
\]
Background measurement

- Want sensitivity to wide range of charges: can also allow slab hits if signal much smaller than muon deposit

- Much smaller background! Motivates four layer design for full detector (see later!)

- Exact signal region definition/predictions being finalised
What level of sensitivity to expect?

NB - this bound assumes a massless dark photon

NB: NPE not calibrated per demonstrator PMT

Expect hits in slab for $Q > \sim 0.02$
Detector simulation

- Full GEANT simulation of milliQan demonstrator
- Models reflectivity, light attenuation length and shape of scintillator
- Input variables: PMT quantum efficiency, light emission spectrum, light yield, surface roughness, …
Calibrating detector simulation

- Validate detector simulation on bench using quad trigger system to assure vertically-travelling muons with specific paths through milliqan bar
- Good agreement for the effective light attenuation length of the scintillator bar
- Work-ongoing to calibrate per-PMT detection efficiency for demonstrator
Comparisons (from pheno paper)

**flattening artificial:**
no mCP production from QCD/hadronic processes included (only DY/prompt resonances)!

Attracting interest in the theory community!