New LHC Experiment: MilliQan

- Milli-charged particles → massive, with electric charge \( \sim 10^{-3} \) e
- Easy to add to SM: “dark U(1)” (with massless dark photon) kinetic mixing → dark fermion milli-charged under SM
- Currently weak direct limits for fermion mass > 100 MeV
- \( \sim 1 \) photo-electron observed per 1m long scintillator
- Require triple-incidence in time window
- Moving forward in CMS “drainage gallery”
MilliQan Theory

\[ \mathcal{L} = \mathcal{L}_{SM} + \mathcal{L}_{DS} \]

\[ \mathcal{L}_{DS} = -\frac{1}{4} A'_{\mu\nu} A'^{\mu\nu} + i \bar{\psi}' \left( \partial + ie' A' + iM_{\psi'} \right) \psi' - \frac{\kappa}{2} A'_{\mu\nu} B^{\mu\nu} \]

\[ \mathcal{L}_{DS} = -\frac{1}{4} A'_{\mu\nu} A'^{\mu\nu} + i \bar{\psi}' \left( \partial + ie' A' + i\kappa e' B' + iM_{\psi'} \right) \psi' \]

- Let us assume that the DS has at least one Abelian gauge group, \( U_{DS}(1) \)
  - Consisting of a massless dark boson \( A'_\mu \), and a dark fermion \( \psi' \) with charge \( e' \) and field strength \( A'_{\mu\nu} = \partial_\mu A'_\nu - \partial_\nu A'_\mu \)
  - Small kinetic mixing with the SM hypercharge \( (B_{\mu\nu}) \) and strength \( \kappa \ll 1 \)
  - A gauge transformation \( (A'_\mu \rightarrow A'_\mu + \kappa B_\mu) \) eliminates the kinetic mixing term, in favor of mixing between the dark fermion and the SM gauge boson

- The dark fermion, \( \psi' \), interacts with the SM \( \gamma(Z) \) with charge \( \kappa e' \cos \theta_w (\sin \theta_w) \) and has mass \( M_{\psi'} = M_{mCP} \)

Note that \( \psi' \) is not, itself, a candidate for THE dark matter
MilliQan Collaboration

- Members of CMS, ATLAS, and “theorists”
- Currently 6 PIs

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MilliQan Site

- “Drainage Gallery” - an interlocked tunnel above CMS Point 5

Beam backgrounds shielded by 14m of rock

30m from interaction point

Small angle from vertical
MilliQan Detector

- Array of plastics scintillators and PMTs, see single photo-electrons from traversing mCPs

The Scintillator

- A MIP with $Q = 1e$ deposits $\sim 2$ MeV/cm in a material with a density of $1$ g/cm$^3$
- For a plastic scintillator, energy deposits result in $\sim 10^4$ photons / MeV
- Putting it together, $2 \times 10^6$ photons would be liberated in a 1m long bar

The PMT

- On average $1/3$ of photons successfully hit the PMT
- The quantum efficiency of the PMT is $\sim 25\%$
- Thus, the overall efficiency is $10\%$, i.e. one photo electron (PE) for every 10 liberated photons

mCP’s

- The deposited energy is proportional to $Q^2$
- For a mCP with $Q = 2.2 \times 10^{-3}e$, we expect 1 PE per bar
MilliQan Trigger and Readout

- Low noise (~0.7 mV RMS)
- Full pulse shape
- Easily observe single PE's
- Good time resolution (~few ns)

Hardware Overview (CAEN V1743):
- 16 analog read-out channels, continuously sampled at 3.2 GS/s into a 1024 cell ring
- Programmable trigger logic, including an external trigger
- Both and internal clock and an external one (for sync-ing multiple boards to the same clock)
- Equipped with both VME and Optical Link interfaces
- Cost per channel is about $400
MilliQan Simulation and Sensitivity

- Full G4 simulation, including magnetic field of CMS
- Sensitivity agrees with earlier estimates

Background is random dark pulses: $O(10)$ events/year
MilliQan Plan / Schedule

- Initial studies / simulations / sensitivity estimates
- Arrangements with CMS and site studies
- Expression of Interest drafted, collaboration formed

- Aim to commission a test slice at the P5 site during 2016 end-of-year shutdown
- Take test data during 2017-18

- Build full detector in 2018
- Install full detector at P5 site in 2020-22 shutdown

- Take 300/fb of data during RunIII in 2022-25
- Discover mCP :)