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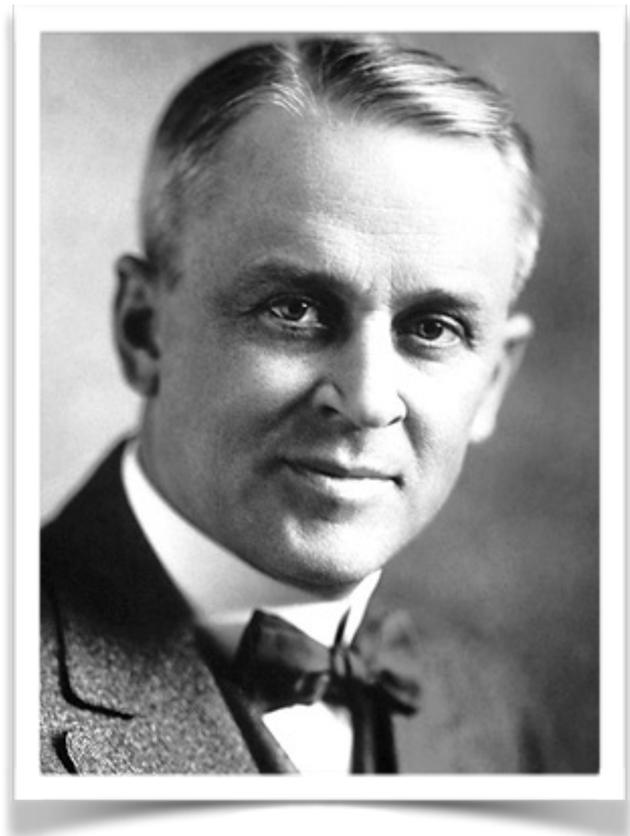
A proposed milli-charged particle detector at LHC Point 5

(which we call ***milliQ**an*)



TeVPA 2017
The Ohio State University
Columbus, OH
August 11, 2017

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

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Millikan

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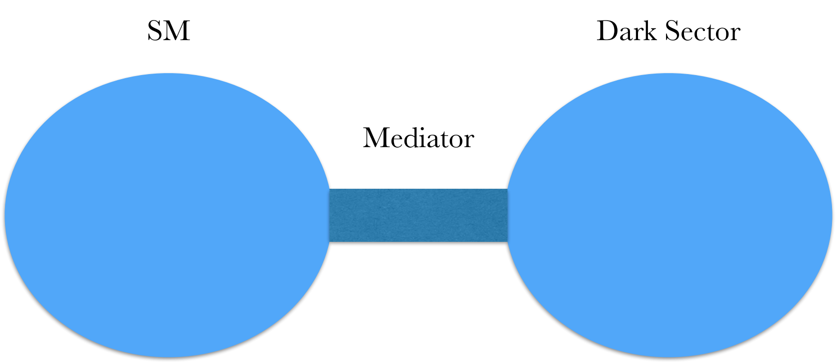
Department of Physics

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



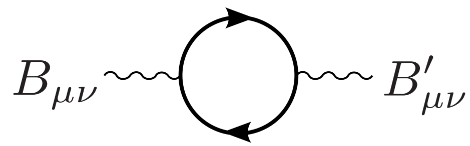
One organizing principle for probing it: focus on lowest-dimension allowed interactions: vector portal, Higgs portal, neutrino portal

$\epsilon_Y B^{\mu\nu} B'_{\mu\nu}$ $\qquad$ $\epsilon_h |h|^2 |\phi|^2$ $\qquad$ $\epsilon_\nu L h \psi$

- 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*



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

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

$$\mathcal{L} = \mathcal{L}_{\rm SM} - \frac{1}{4}B'^{\mu\nu}B'_{\mu\nu} - \frac{\kappa}{2}B'^{\mu\nu}B_{\mu\nu} + i\bar{\psi}(\partial\!\!\!/ + ig_D B\!\!\!/' + iM_{\rm mCP})\psi$$

$$B'_\mu \to B'_\mu + \kappa B_\mu$$

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

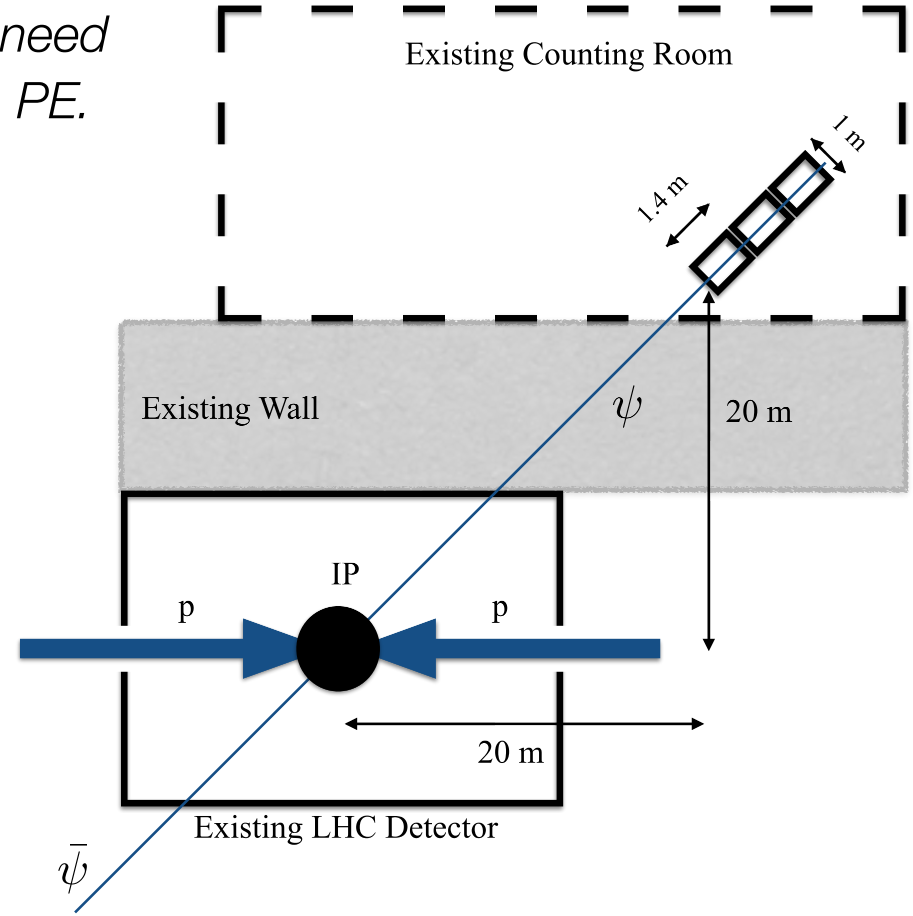
After electro-weak symmetry breaking DS fermions acquire an EM charge

$$Q = \kappa g_D \cos\theta_W$$

(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 ~10^{-3}e, dE/dx is 10^{-6} MIP -> need large, sensitive, active area to see signal, $\mathcal{O}(1)$ PE.*
- Install ~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

Andrew Haas,[1] Christopher S. Hill,[2] Eder Izaguirre,[3] and Itay Yavin[3,4]
[1]*Department of Physics, New York University, New York, NY, USA*
[2]*Department of Physics, The Ohio State University, Columbus, OH, USA*
[3]*Perimeter Institute for Theoretical Physics, Waterloo, Ontario, Canada*
[4]*Department of Physics, McMaster University, Hamilton, ON, Canada*

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.

arXiv:1410.6816v1 [hep-ph] 24 Oct 2014

Where could we put such a detector?

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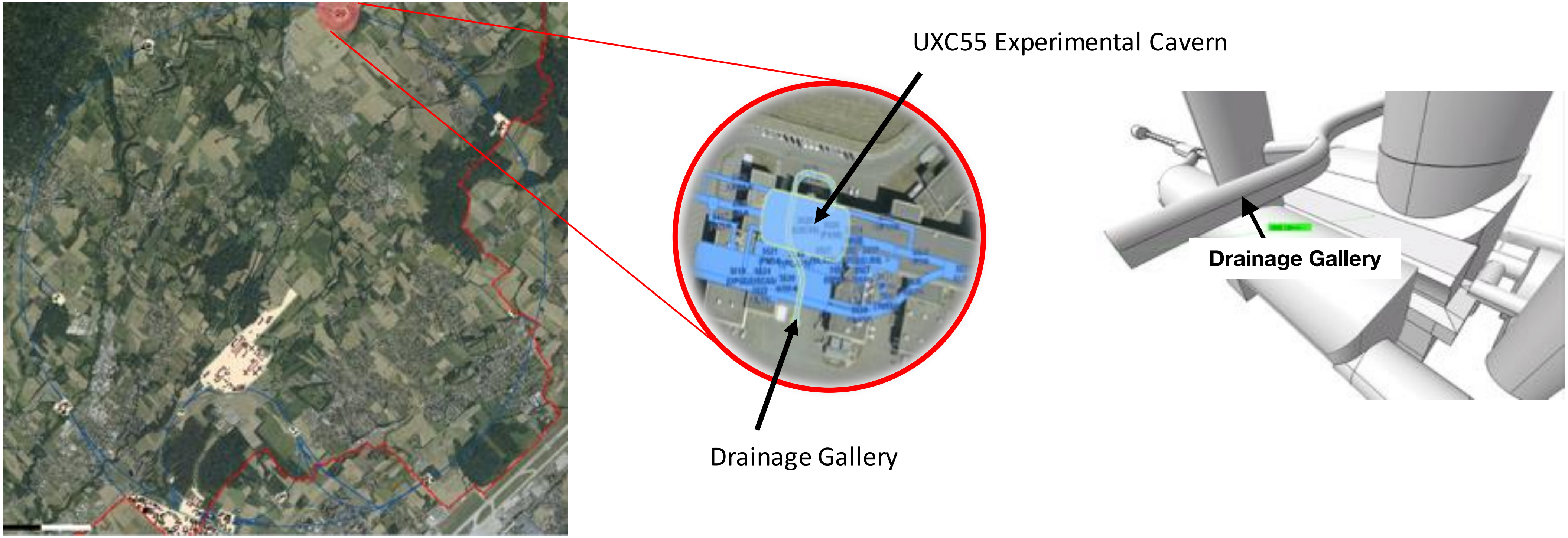
- **Constraints:**
  - *Behind at least 5m of concrete/rock from the IP*
  - *Space to accommodate the detector (~1m x 1m x 3m)*
  - *Floor loading compatible with detector+support structure (up to 6000 kg)*
  - *Power available, with possibility to add other services*
  - *Selected experimental area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

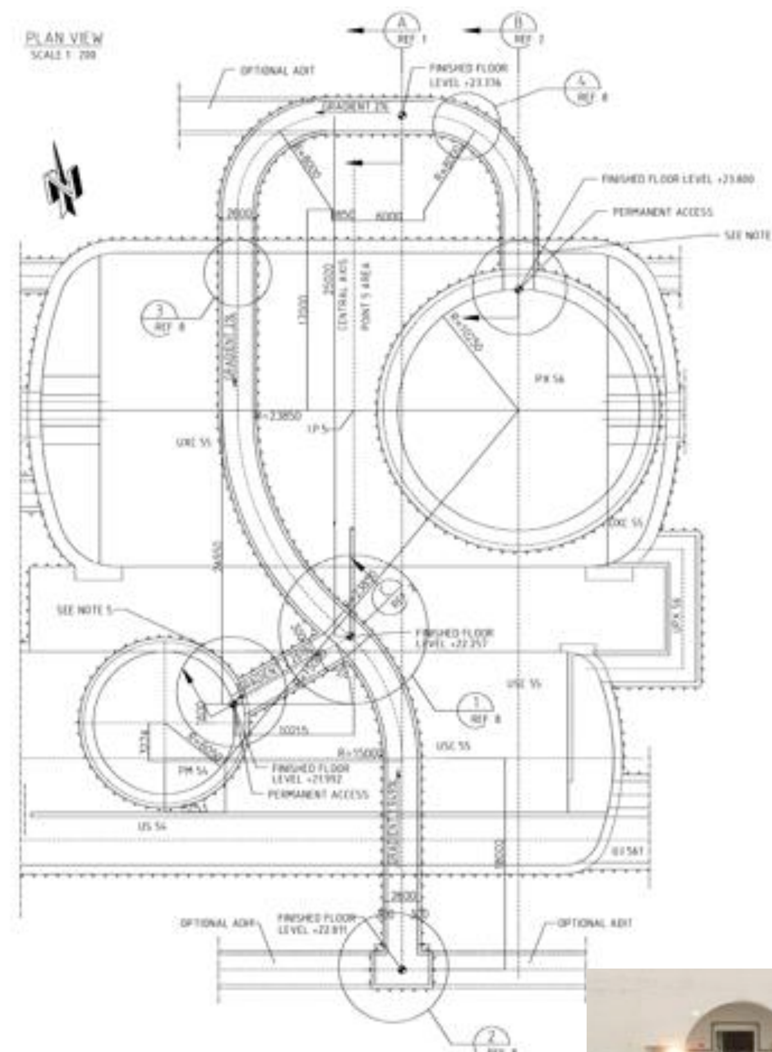


- The PX56 drainage gallery was used during the excavation phase of the CMS experimental area.
- It links the 2 CMS shafts PM54 and PX56 together

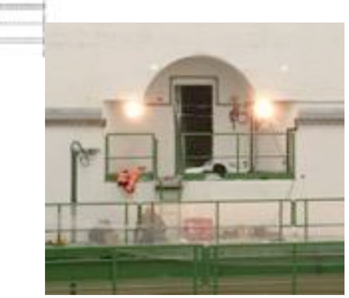
PX56 Observation and Drainage gallery

- 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?

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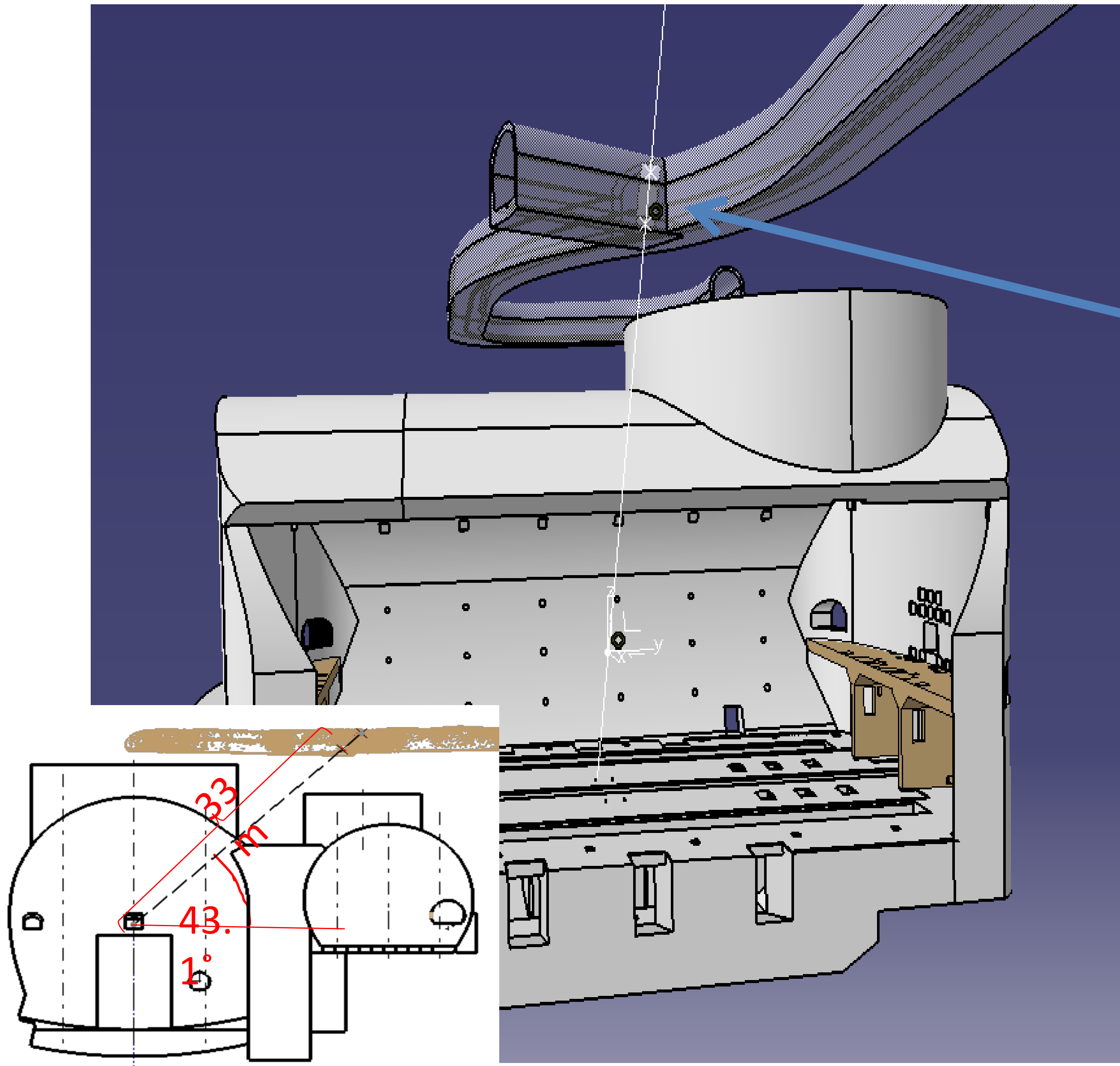
- Sensitivity of experiment ∝ length of scintillator
  - *want to maximize what can fit in dimensions*
- Sensitivity of experiment ∝ 1/(distance from IP)^2,
  - *want to minimize this distance, while satisfying above*
- Optimized location found:
  - *33 m from IP*
  - *17 m through rock*
  - *Angle from horizontal plane is 43.1 deg*



Alignment to CMS IP

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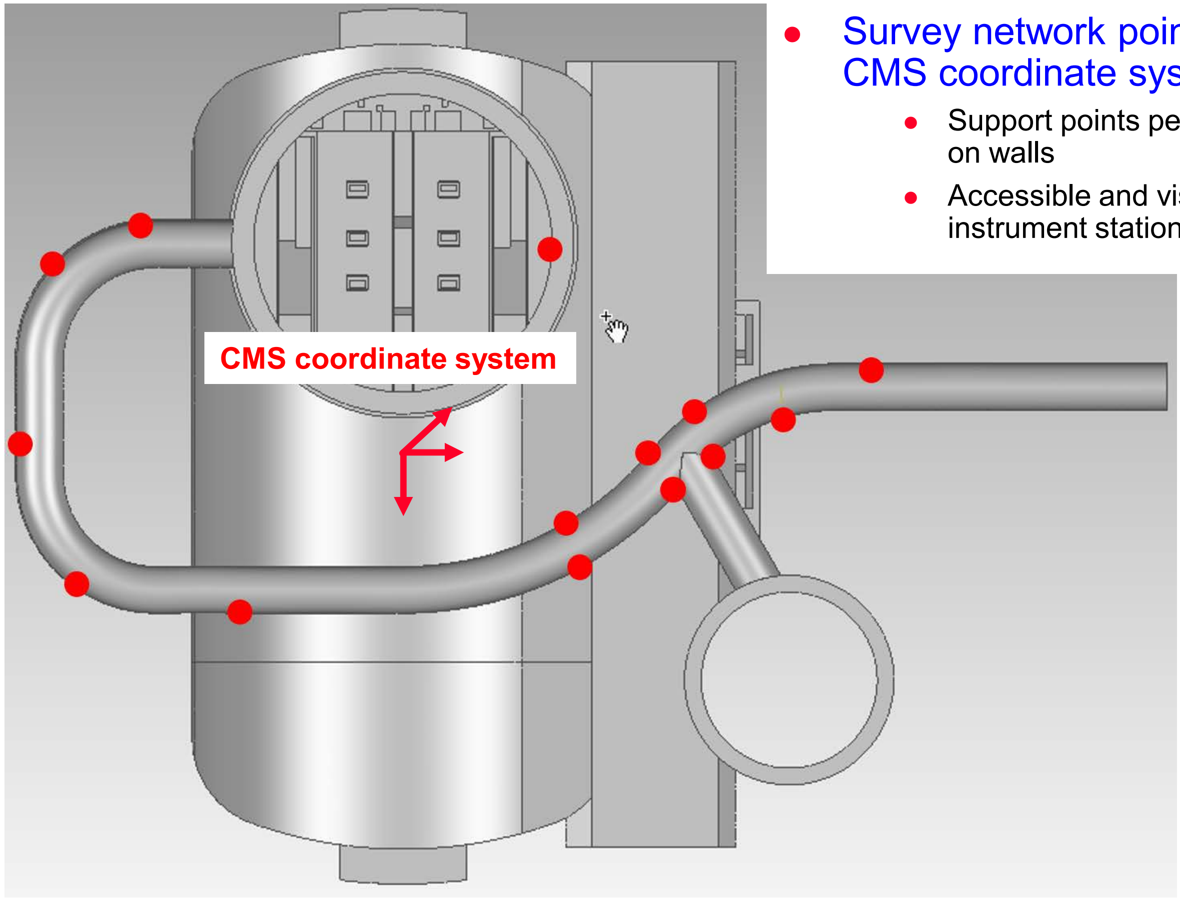
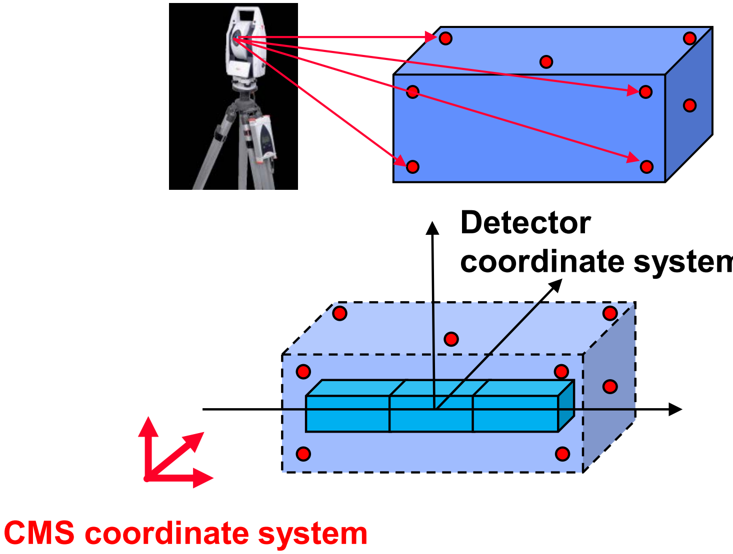
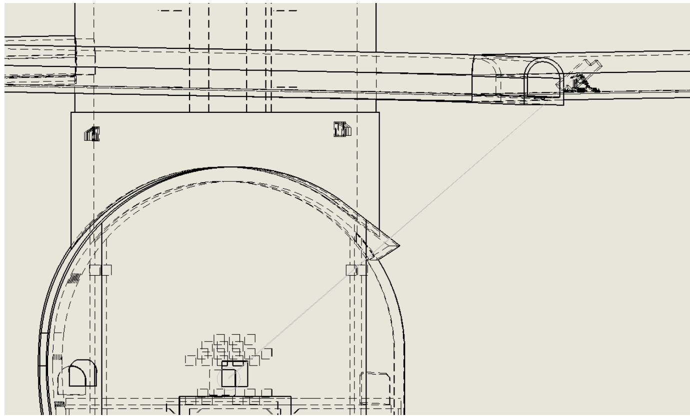
Survey network points installed in drainage gallery



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





Aligned in the Vertical direction

- Allows initial alignment good to < ~cm (over 33 m!)
  - *Final alignment using muons from IP*

Overview of Proposed Detector

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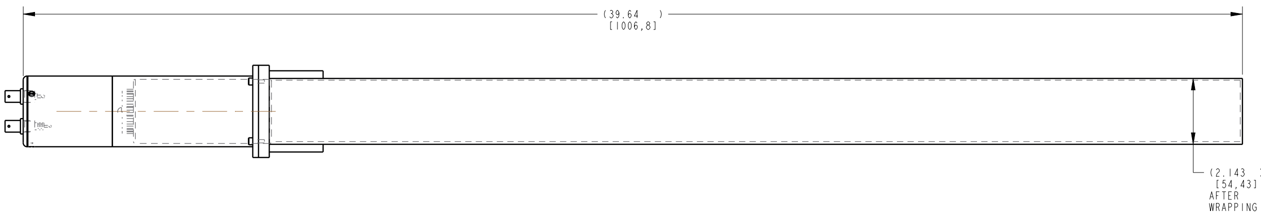
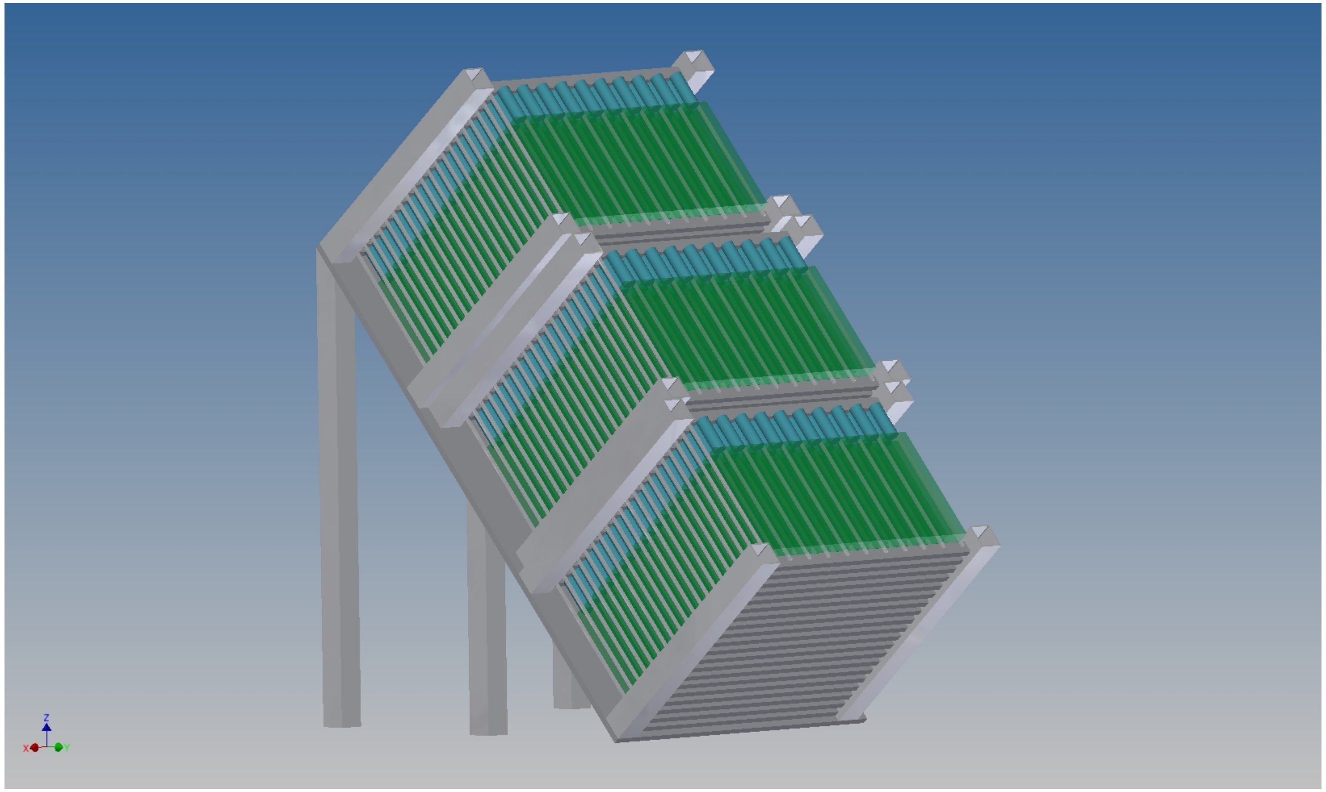
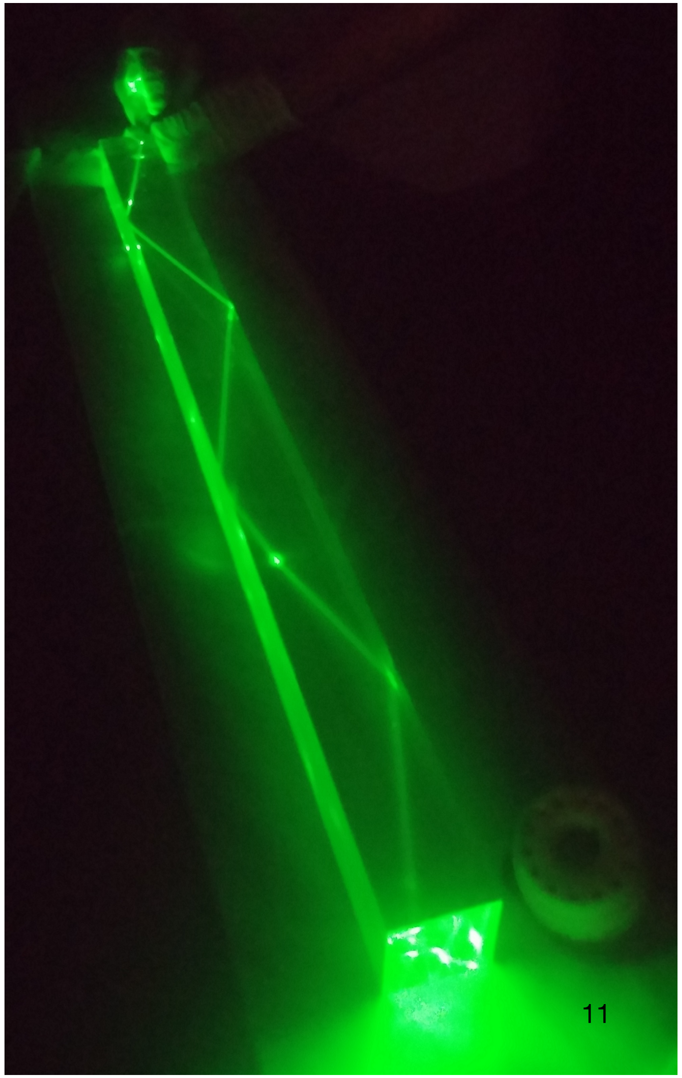
- Basic element is a 5 cm^2 x 80 cm bar pf plastic scintillator (BC 408) + PMT (HPK R7725)
- Arranged in a 20 x 20 x 3 array
  - *Supported by movable mechanical structure*
    - **Alignment to IP + retraction to allow passage through gallery**







Expected Backgrounds

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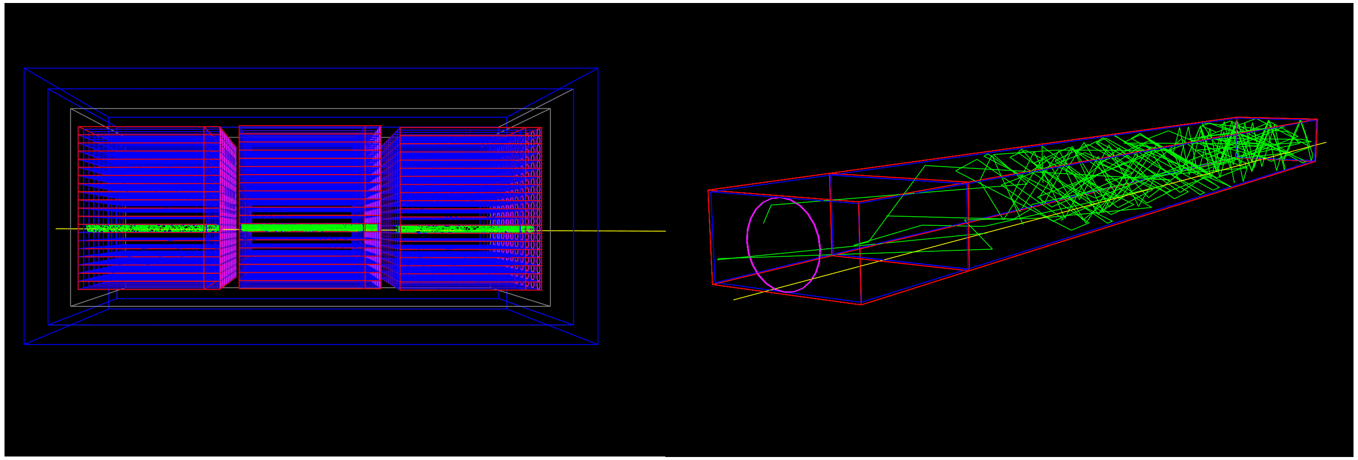
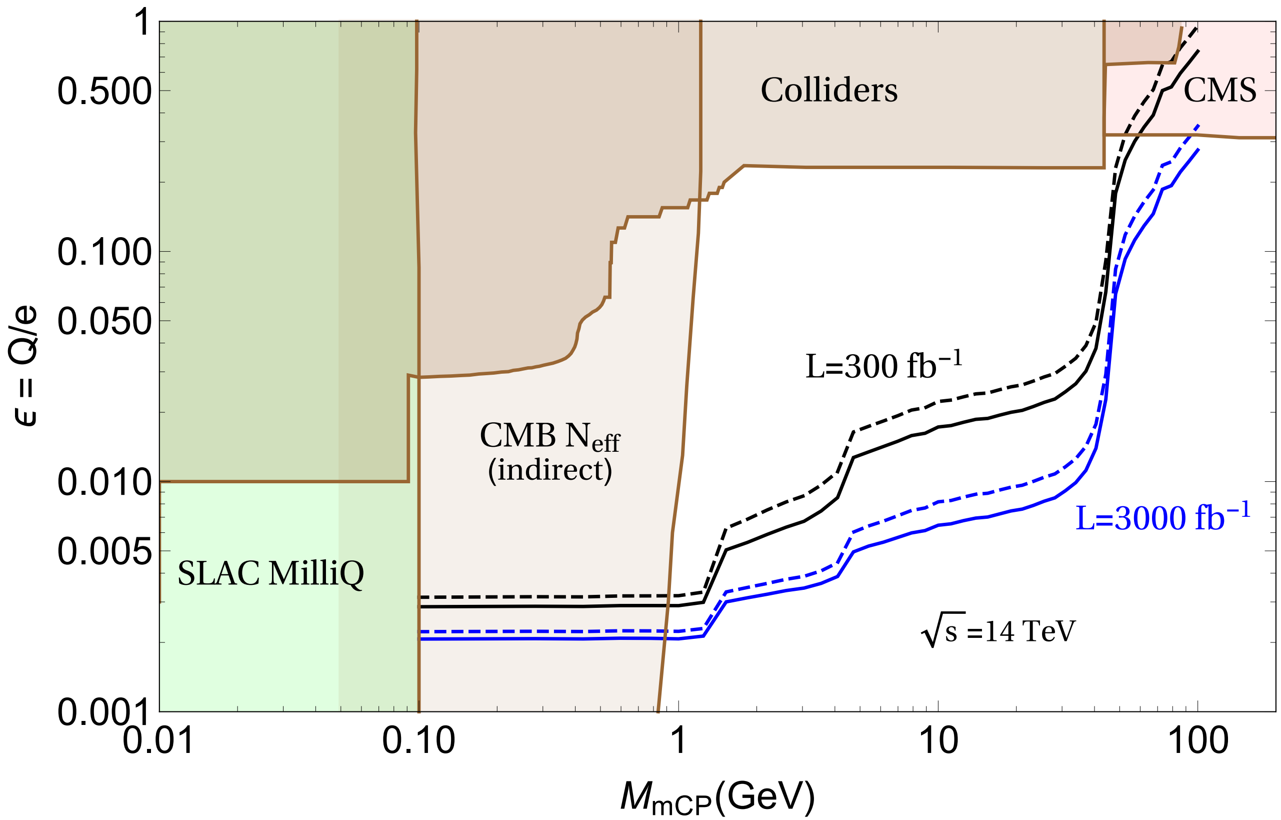
- Expect 17 m of rock will shield particles form pp collision (except muons) to negligible levels
- Muons (from LHC or cosmics) not actually a background since will be very bright (~1M photons in scintillator)
  - *They will be a small source of dead time though*
- Expect irreducible background to be 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***

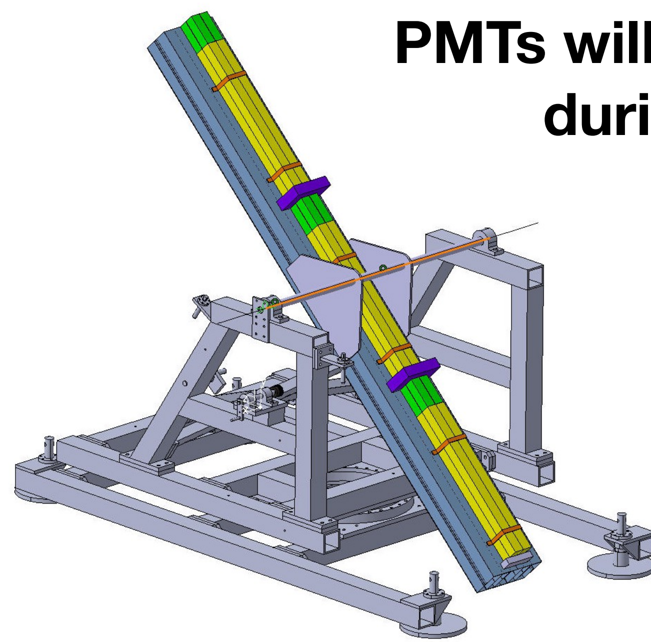




Timeline & Next Steps

- **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,[8] and Itay Yavin[7,6]

[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*

(Dated: July 19, 2016)

Prototype coming together ….

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- 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

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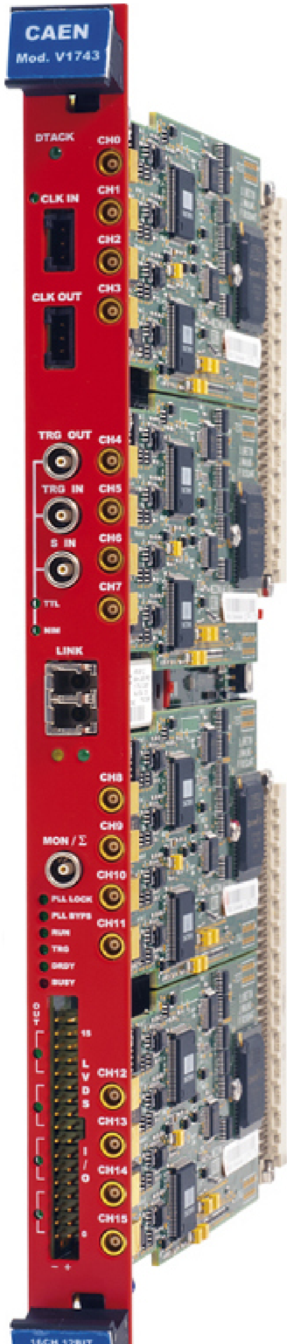
- **milliQan** is a proposed dedicated experiment that would detect **millicharged particles** produced by pp collisions at **LHC point 5**
- The experiment would be **installed during LS2 in a vestigial drainage gallery** above CMS
- Our initial calculations+simulations indicate that with 300 fb^{-1} 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

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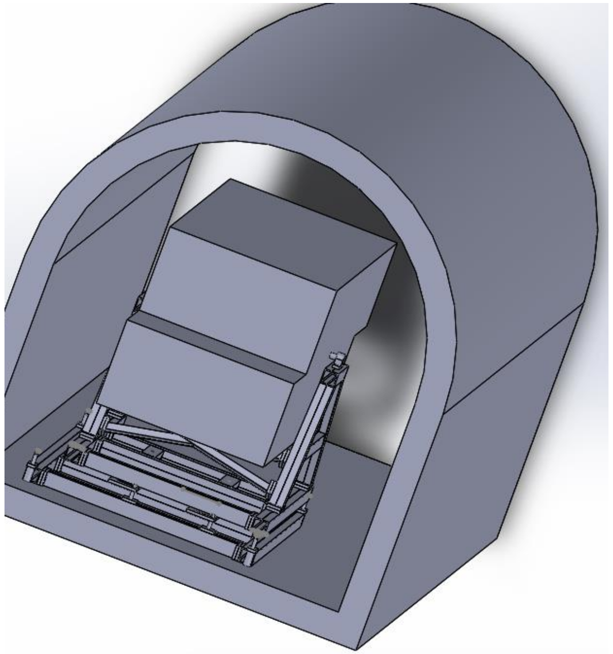
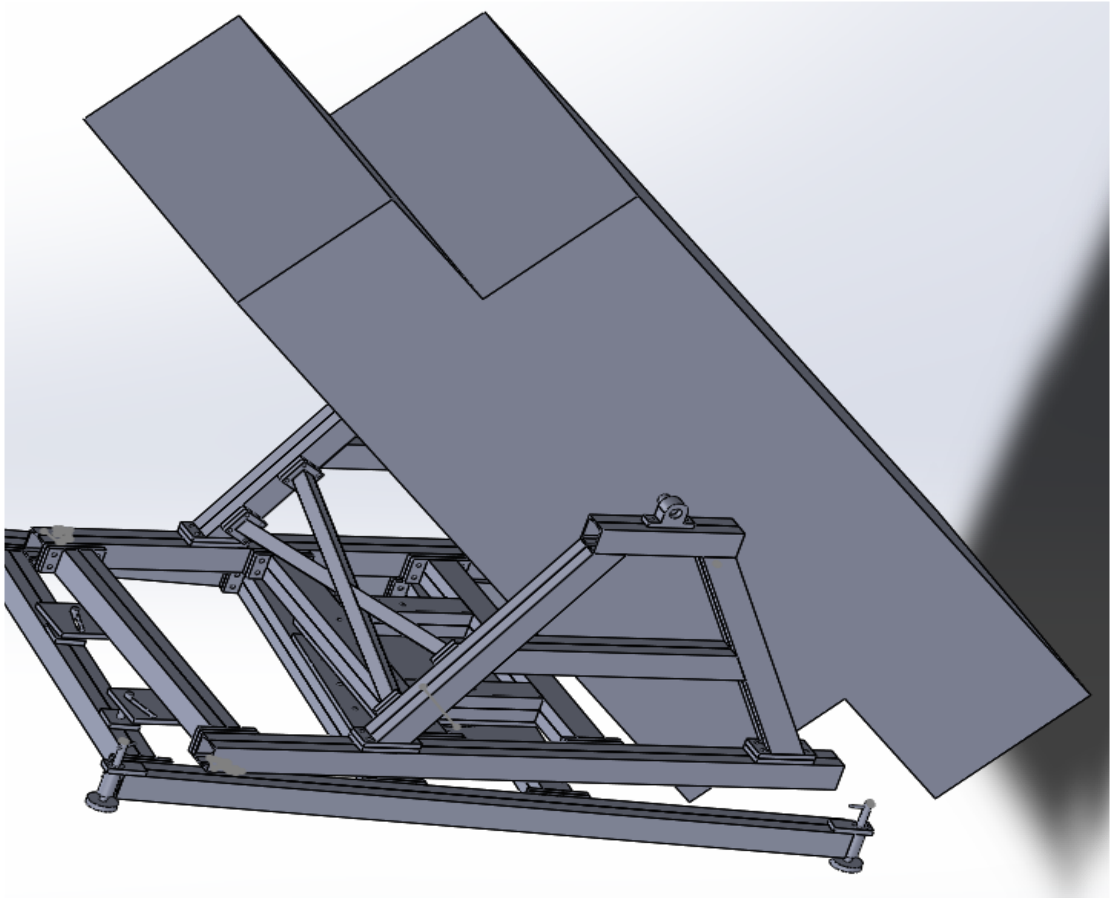
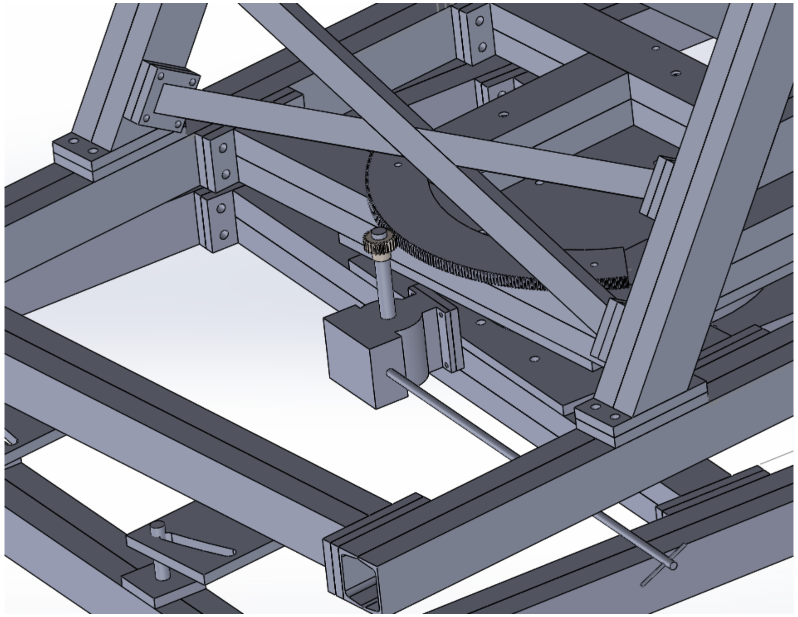
- M. Gastal, R. Loos (CERN) working with engineers from Lebanese University on support structure
    - *Splitting in 2 gives much more clearance*

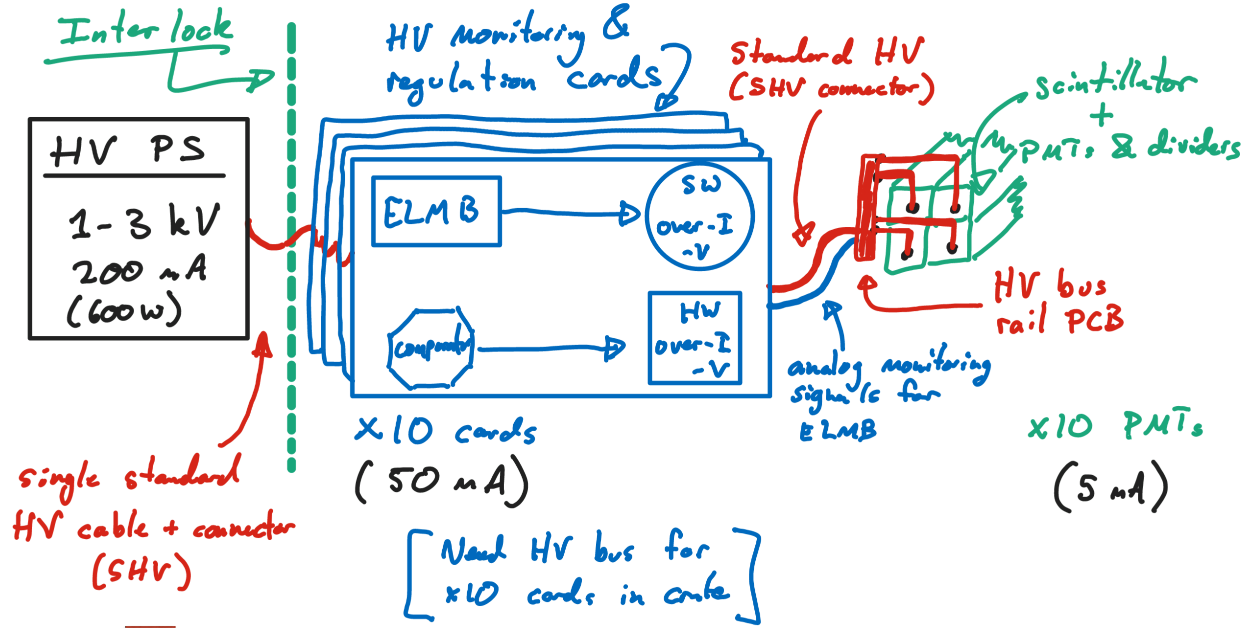


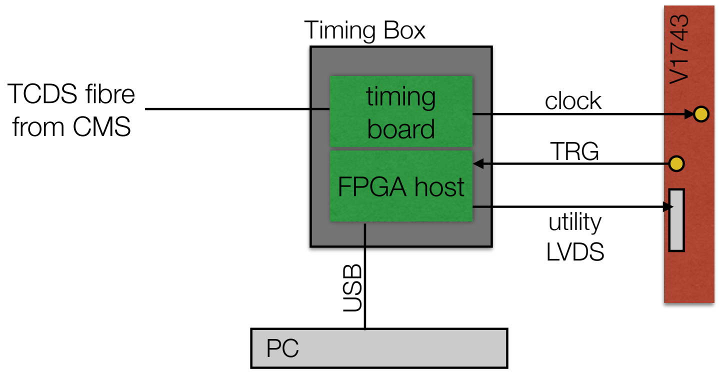


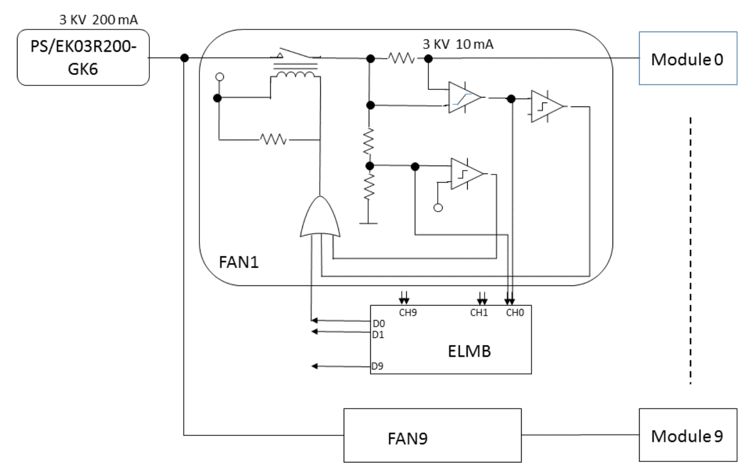


Powering, Slow Controls, Monitoring, Timing

- 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)*



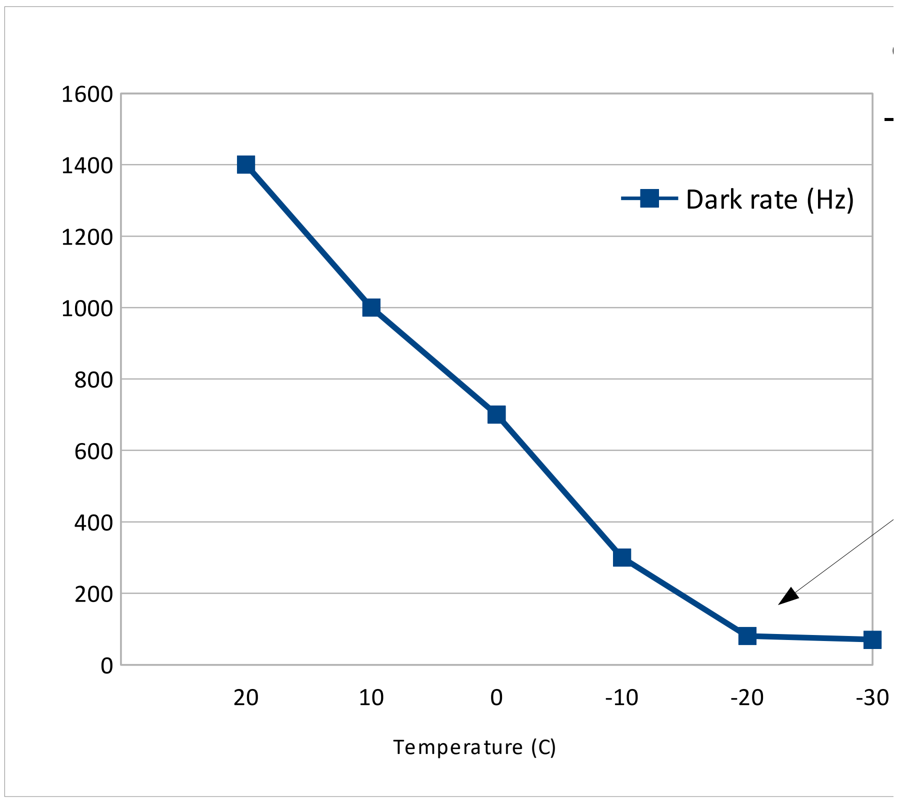


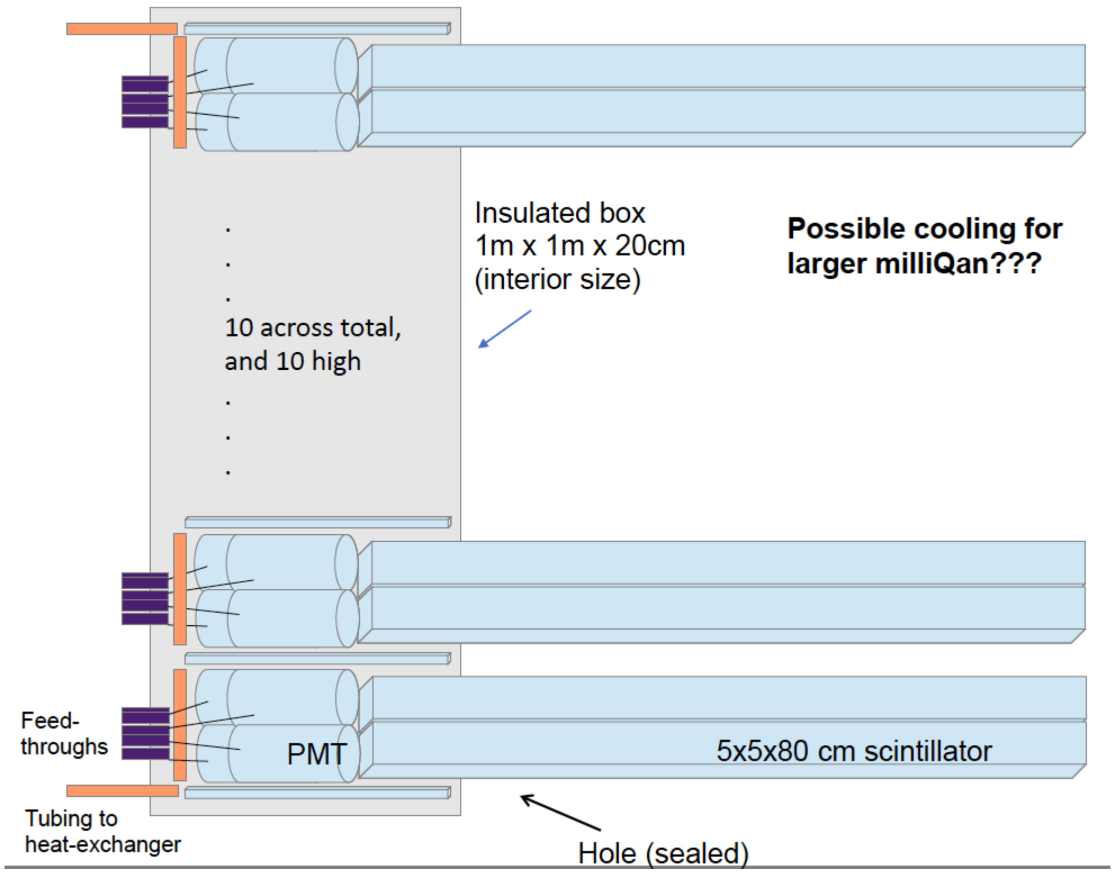


- Timing box receives TCDS fibre from CMS
- Recover LHC clock and send to V1743
- Decode CMS run/lumi/orbit signals
- Receive trigger from V1743, and readout data to PC

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**





Current composition of milliQan

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- **~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