THE OHIO STATE UNIVERSITY

A milli-charged particle detector at LHC Point 5

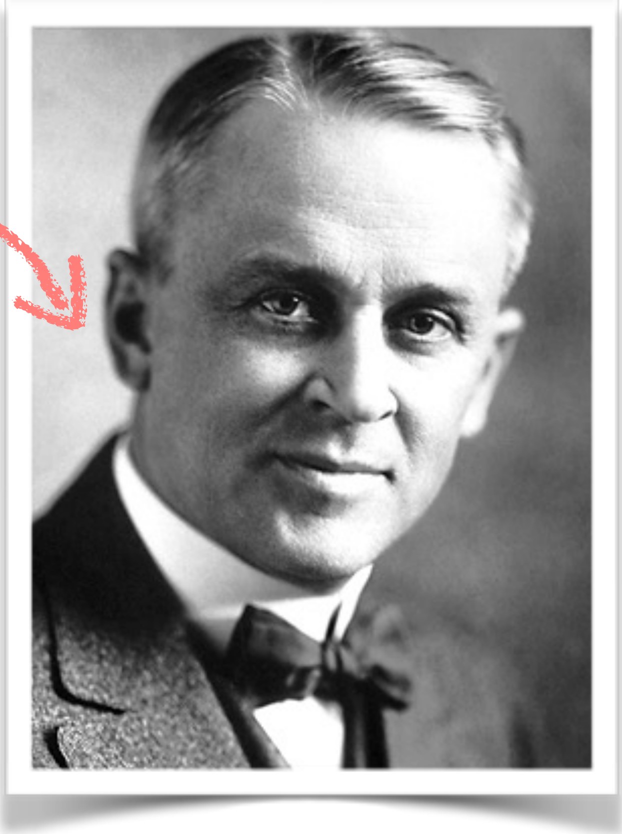
(which we call ***milliQ****an*)

25th Anniversary Rencontres du Vietnam
Windows on the Universe
Quy Nhon, Vietnam
August 15-11, 2018

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

THE OHIO STATE UNIVERSITY

Millikan



A milli-charged particle detector at LHC Point 5

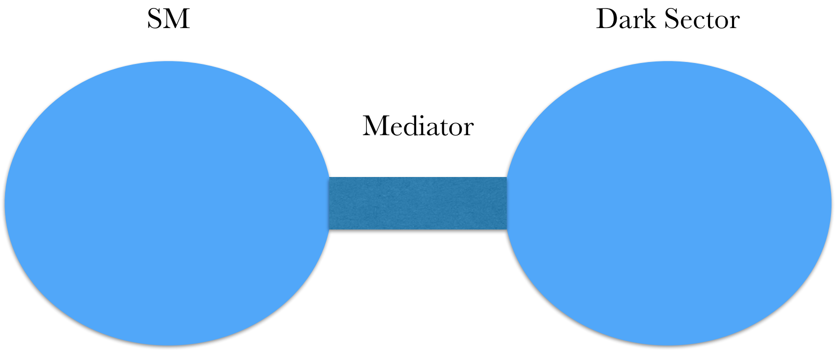
(which we call ***milliQ**an*)

25th Anniversary Rencontres du Vietnam
Windows on the Universe
Quy Nhon, Vietnam
August 15-11, 2018

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

Summer 2014 … were we ready for Run 2 of LHC?

- That summer, at a workshop at ICTP in Trieste, I gave 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



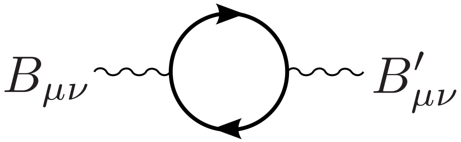
One organizing principle for probing it: focus on lowest-dimension allowed interactions:
vector portal, Higgs portal, neutrino portal

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

- 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*



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

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

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

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

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

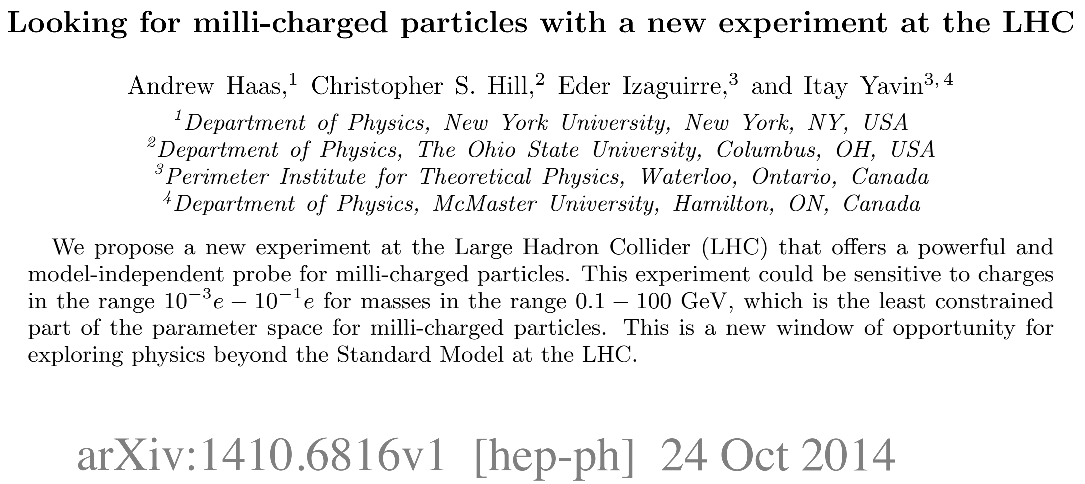
After electro-weak symmetry breaking DS fermions acquire an EM charge

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

(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 long, sensitive, active length 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



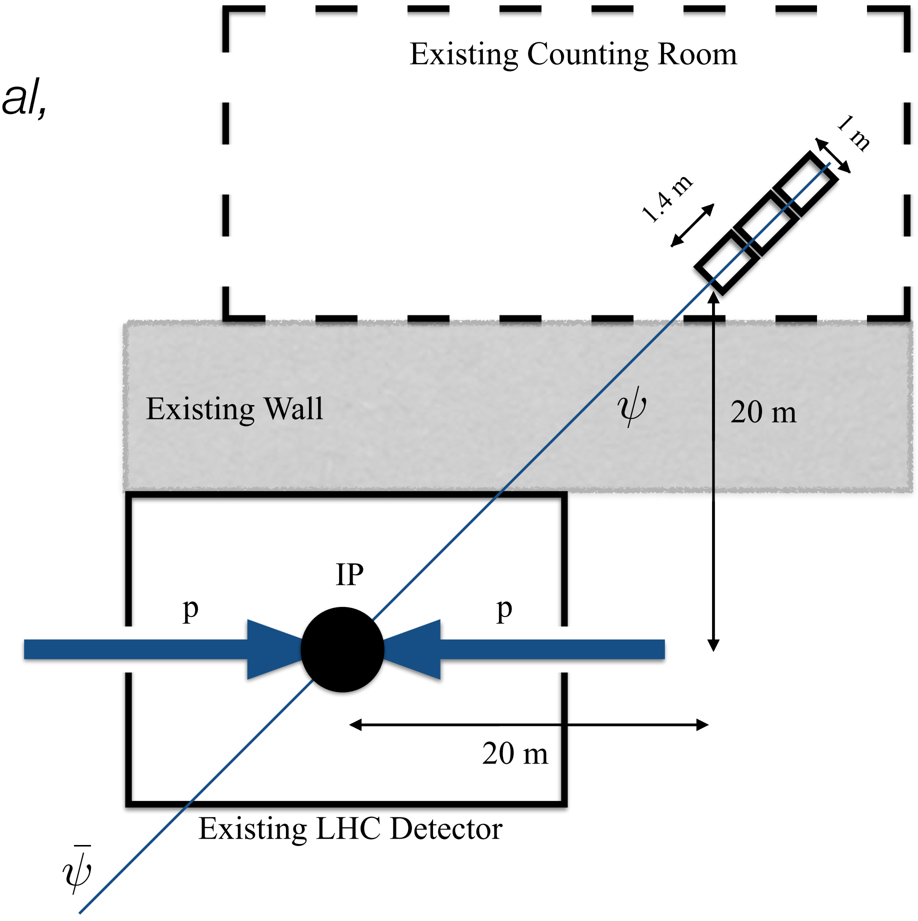
Looking for milli-charged particles with a new experiment at the LHC

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

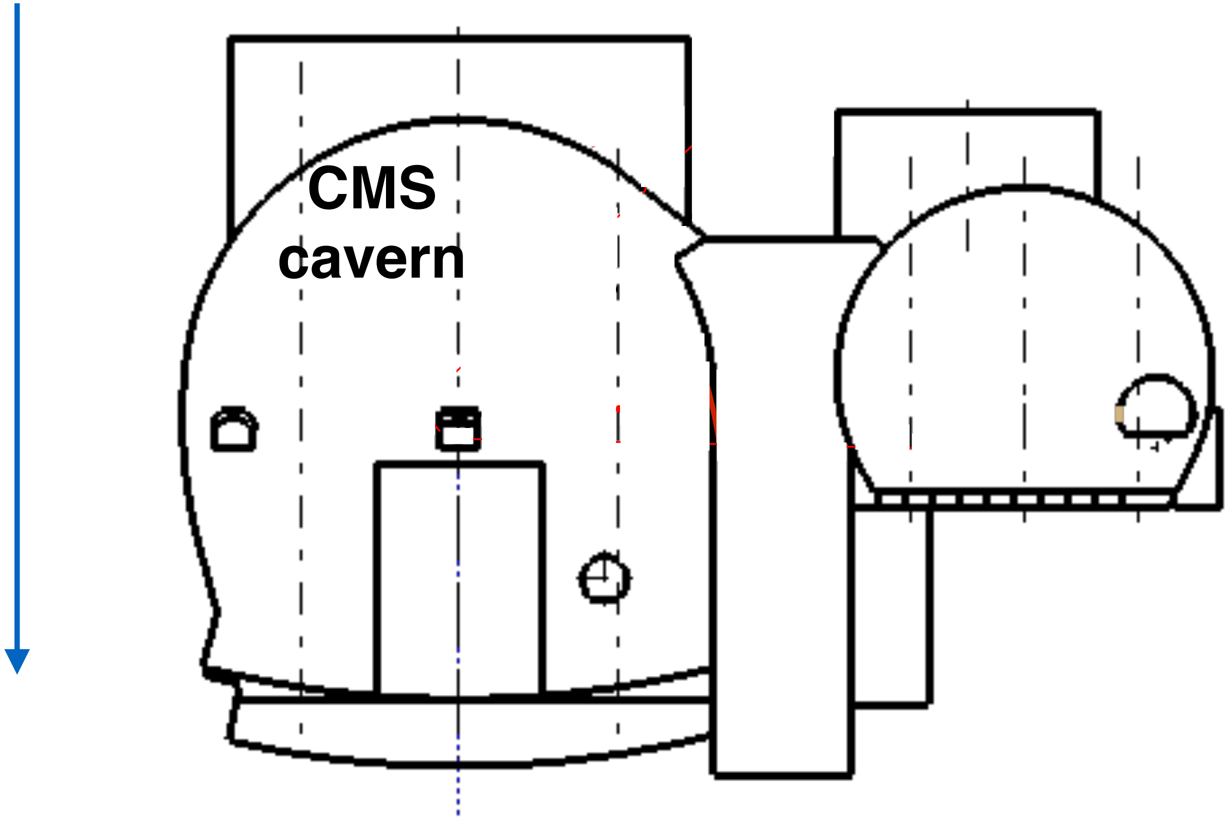


Where could we put such a detector?

- **Constraints:**
    - *Behind at least 5 m 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 did not have an adequate space**
- MoEDAL experiment (based on our paper) is planning on 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)*

Detector Location

100 m underground



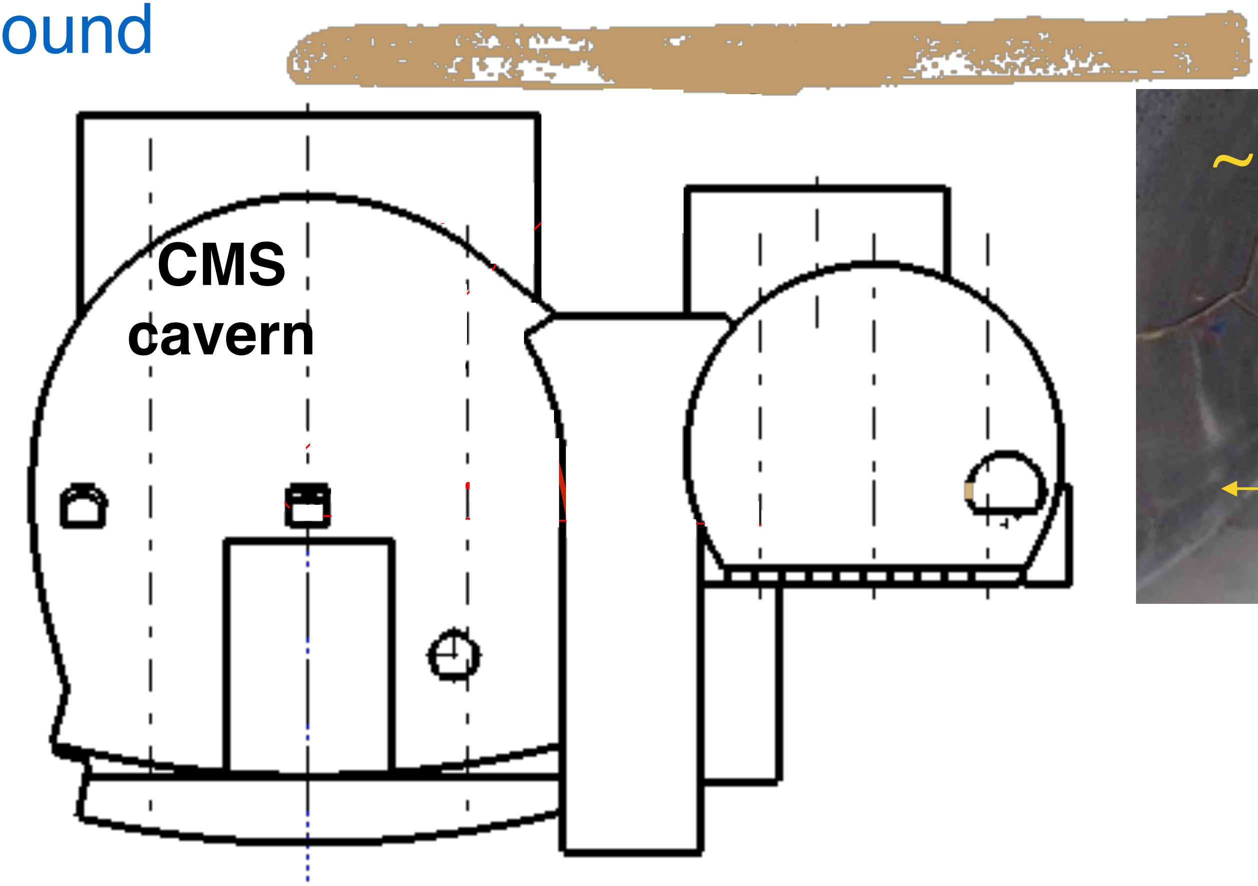
maximize

- Sensitivity of experiment $\propto$ length of scintillator
- Sensitivity of experiment $\propto$ 1/(distance from IP)^2,

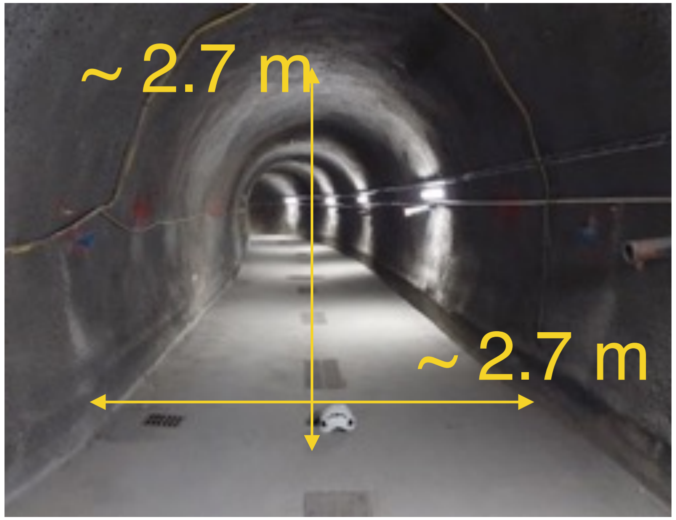
minimize

Detector Location

100 m underground



Drainage gallery



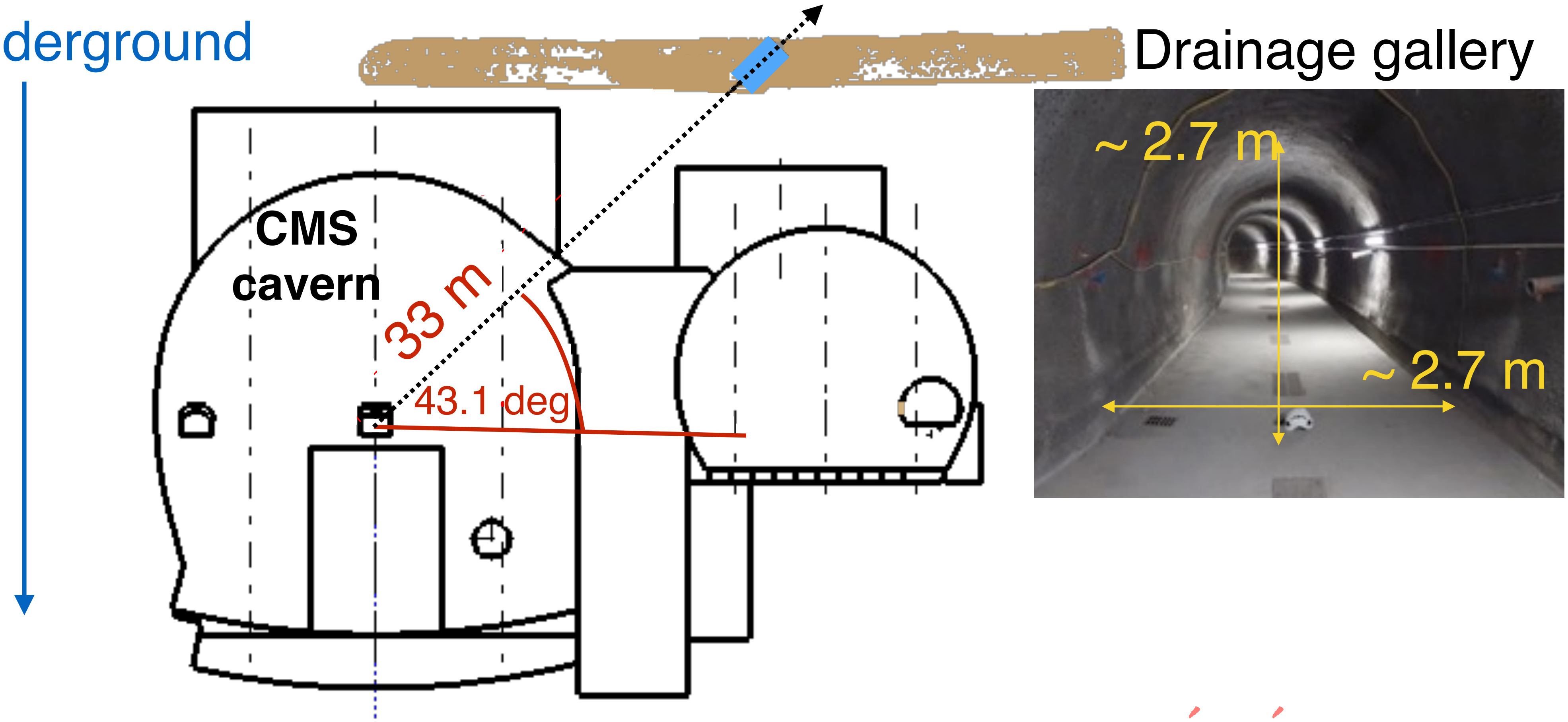
maximize

- Sensitivity of experiment ∝ length of scintillator
- Sensitivity of experiment ∝ 1/(distance from IP)^2,

minimize

Detector Location

100 m underground



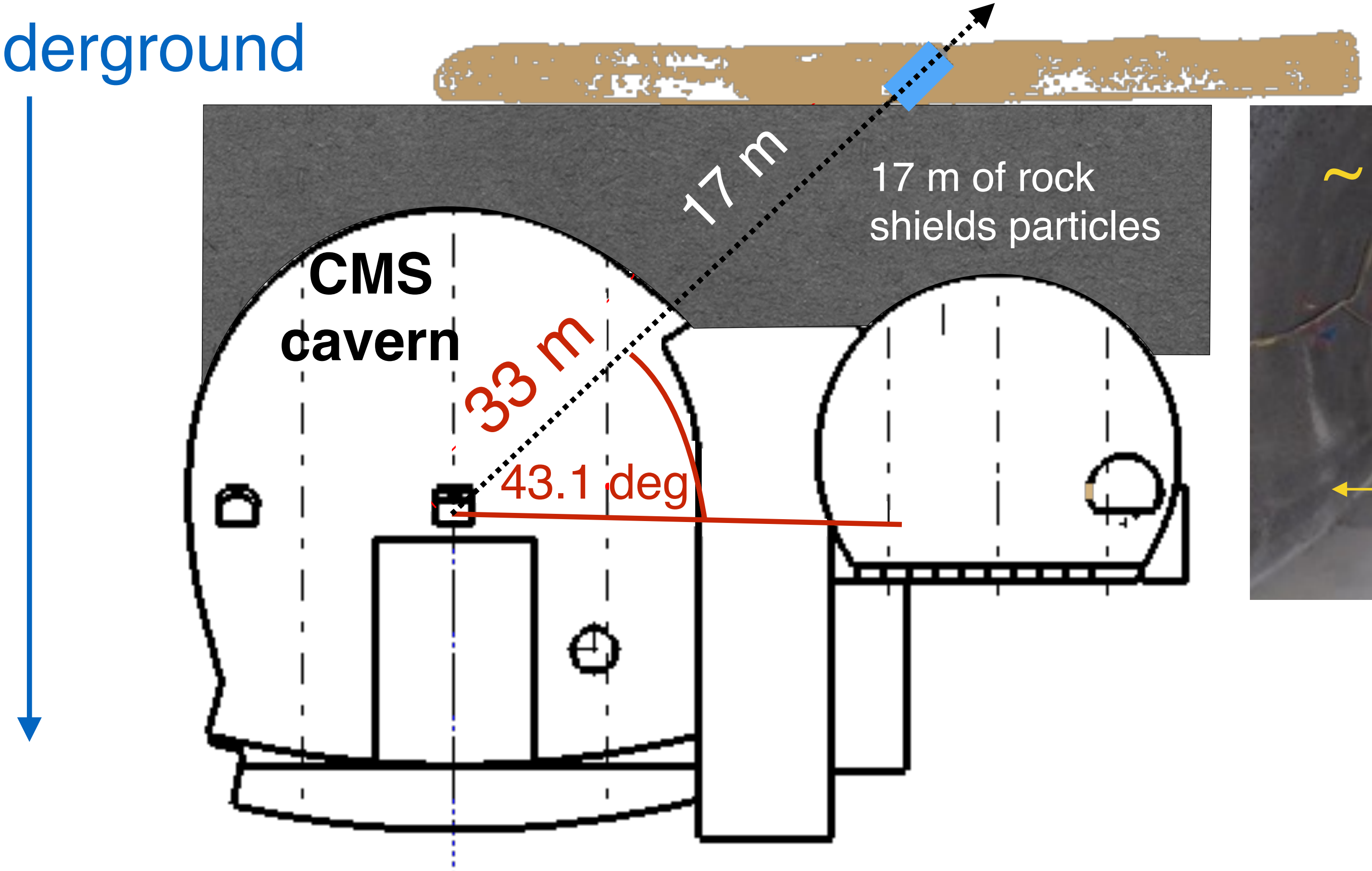
maximize

- Sensitivity of experiment ∝ length of scintillator
- Sensitivity of experiment ∝ 1/(distance from IP)^2,

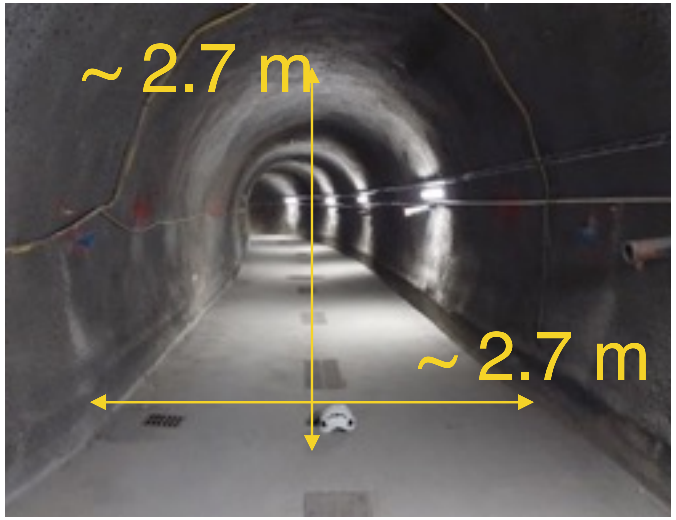
minimize

Detector Location

100 m underground



Drainage gallery

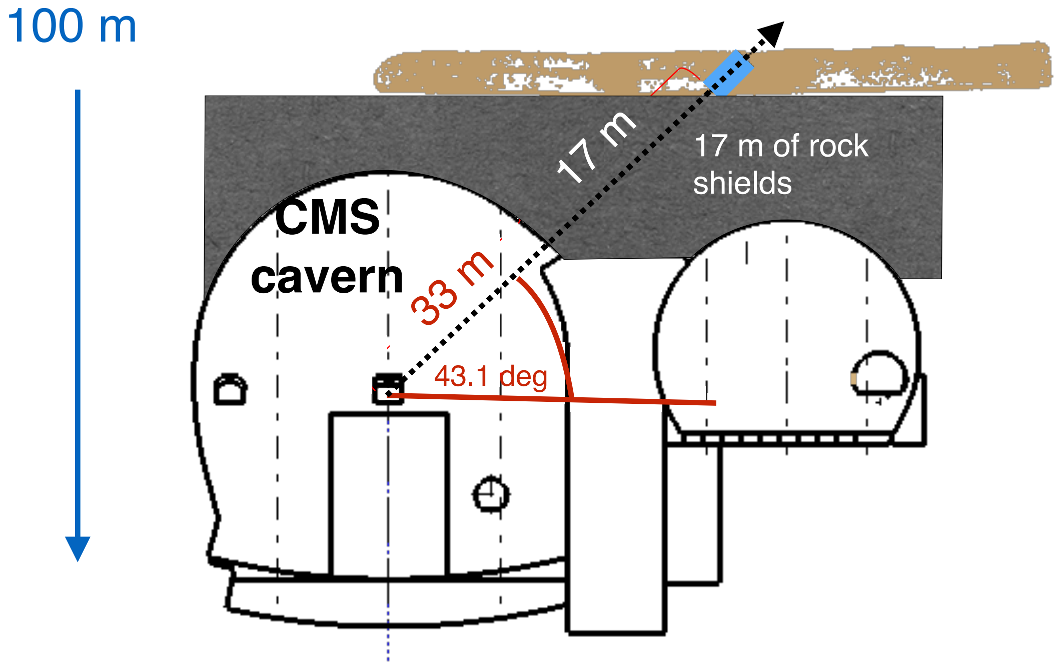


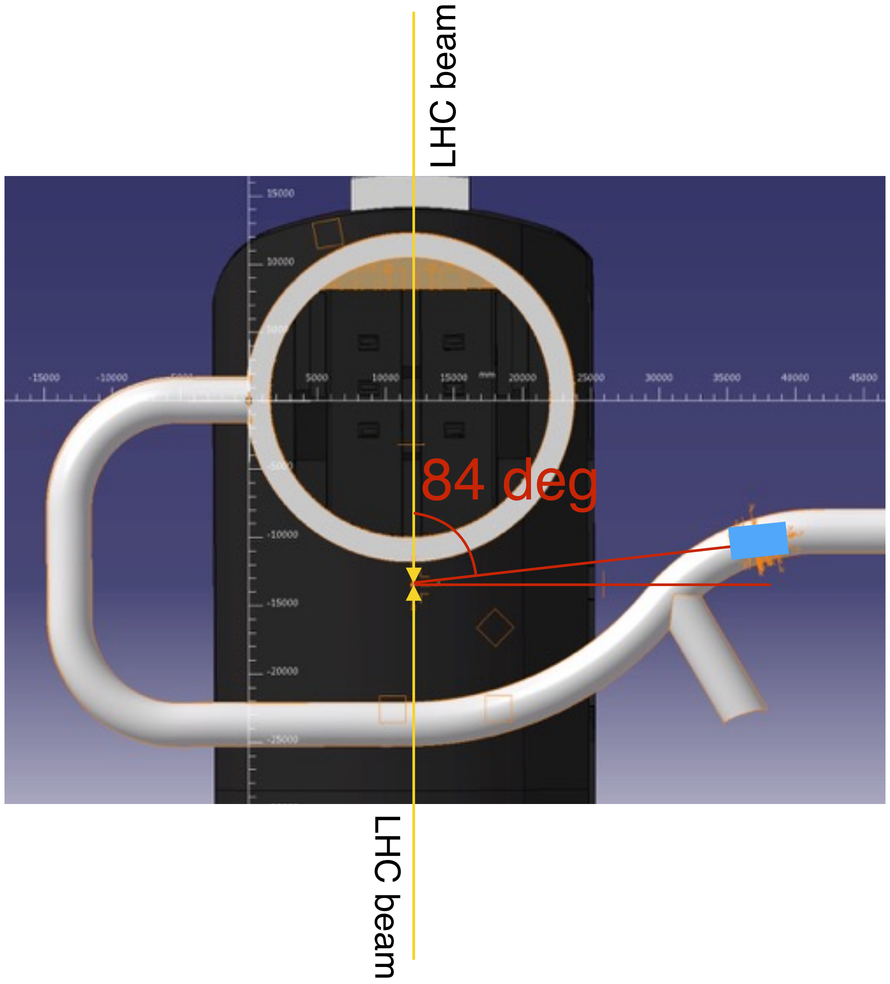
maximize

- Sensitivity of experiment ∝ length of scintillator
- Sensitivity of experiment ∝ 1/(distance from IP)^2,

minimize

Detector Location





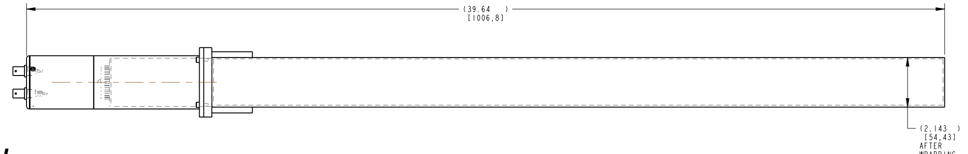
maximize

- Sensitivity of experiment ∝ length of scintillator
- Sensitivity of experiment ∝ 1/(distance from IP)^2,

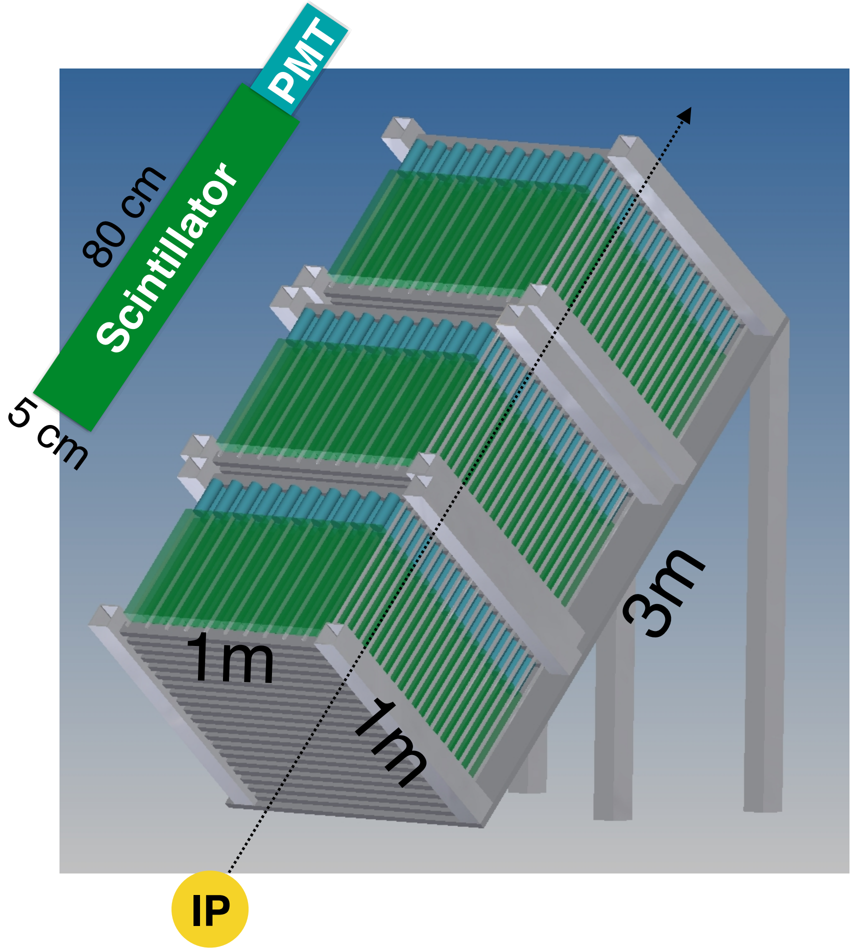
minimize

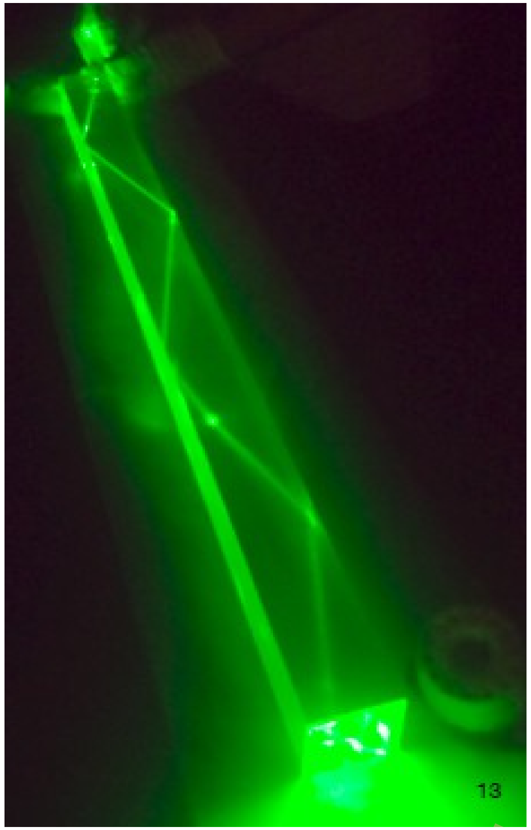
Detector Concept

- Basic element is a 5 cm^2 x 80 cm bar pf plastic scintillator (BC 408) + PMT (HPK R7725)



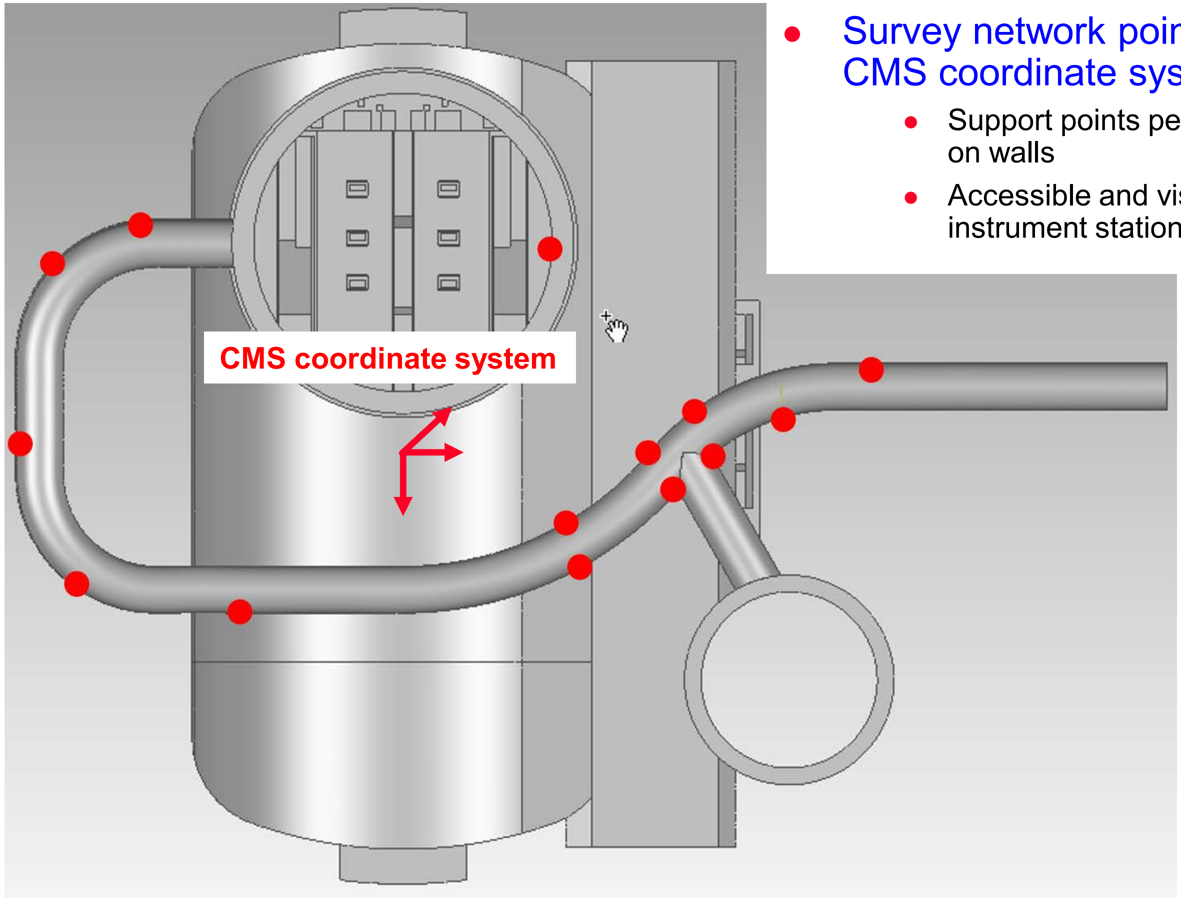
- Arranged in a 20 x 20 x 3 array
  - *Supported by movable mechanical structure*
    - **Alignment to IP + retraction to allow passage through gallery**



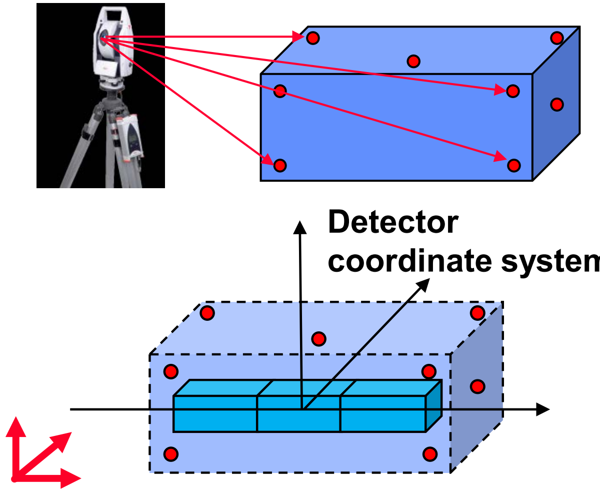


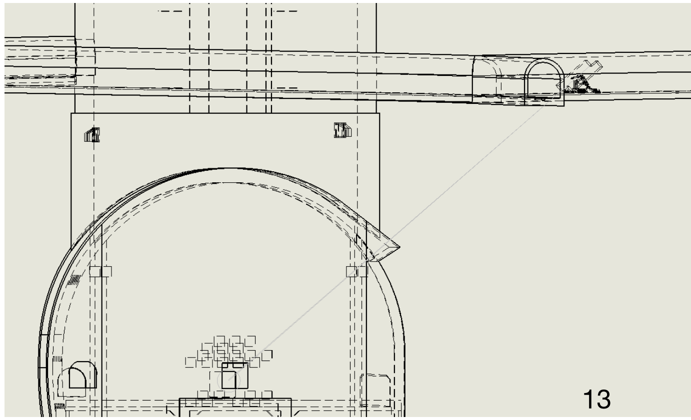
Alignment to CMS IP (without line-of-sight)

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



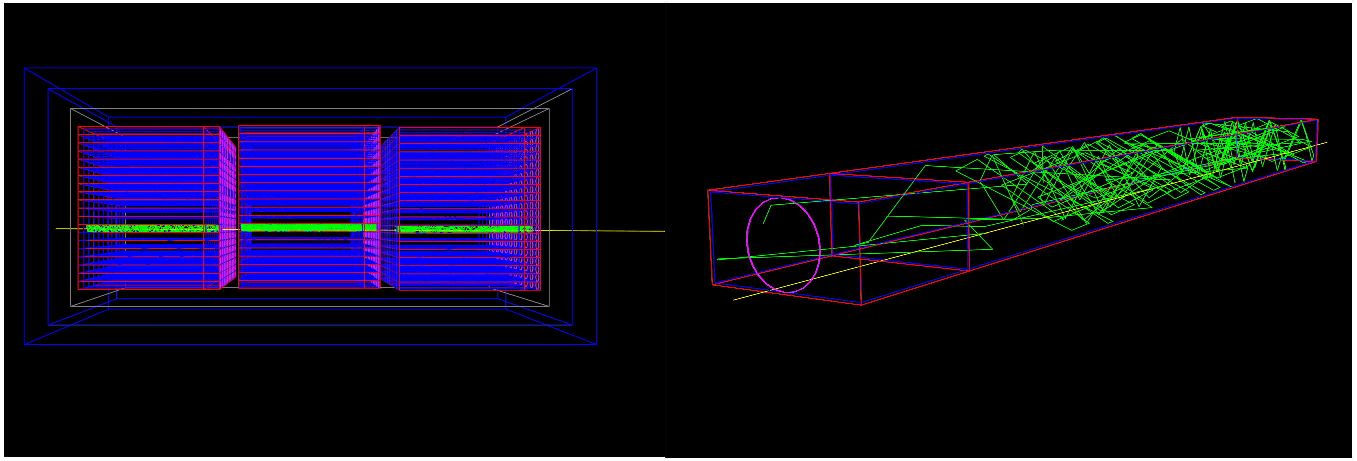


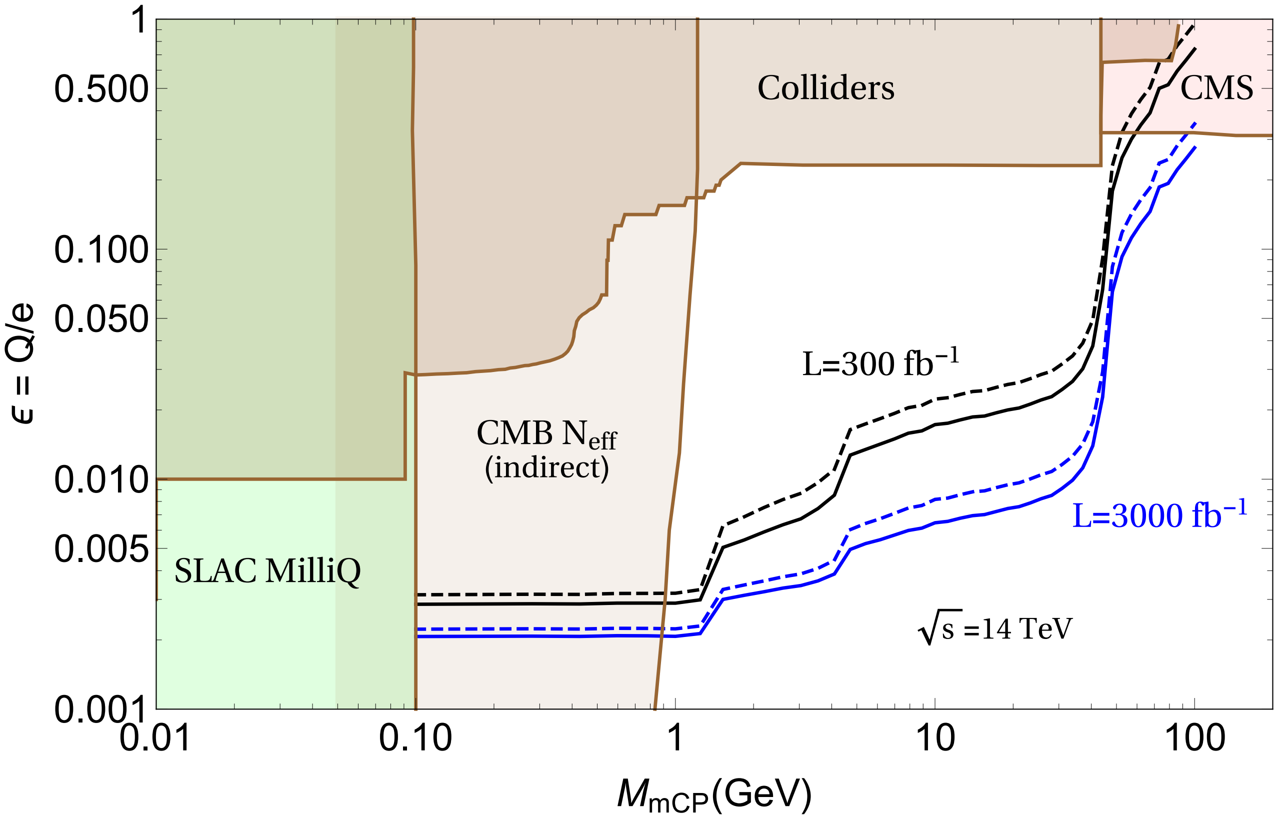
Aligned in the Vertical direction

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

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***

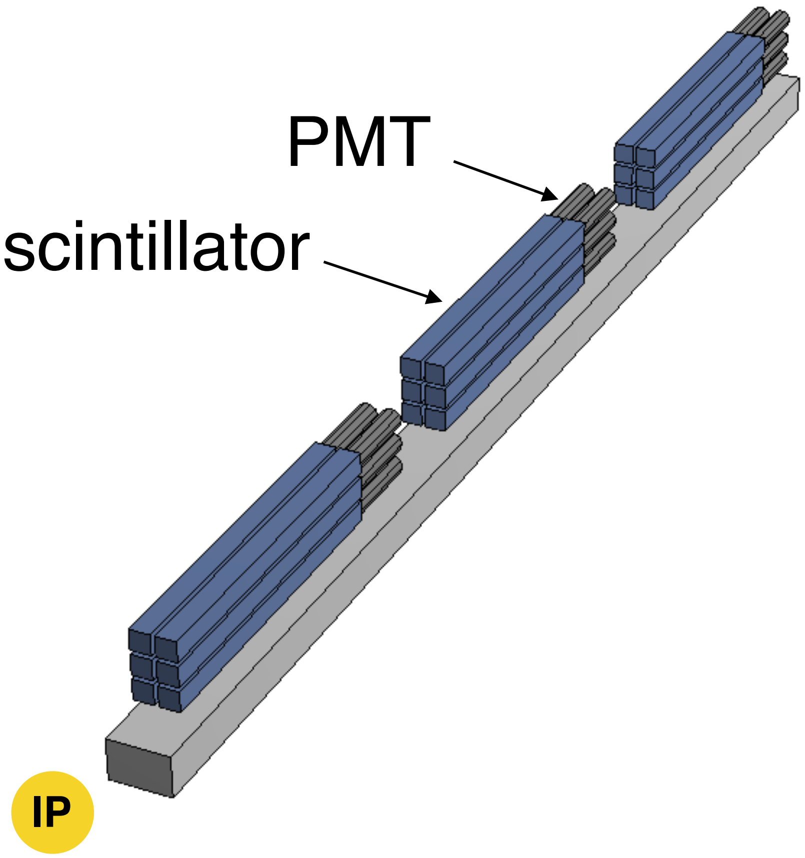




Expected Backgrounds

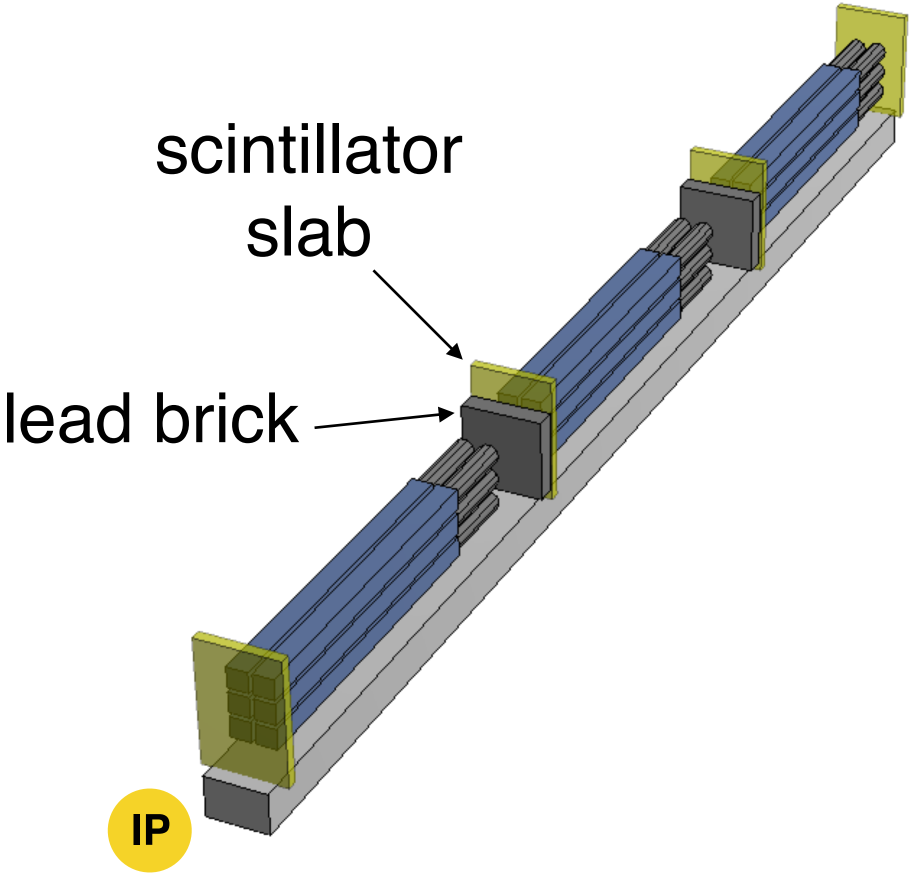
- Expect 17 m of rock will shield particles form pp collision (except muons) to negligible levels
- Muons (from LHC or cosmics) not actually a background since will be very bright (~1M photons in scintillator)
  - *They will be a small source of dead time though*
- Expect irreducible background to be 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
- Background rate can be monitored *in situ* during beam-off periods
- Best way to understand backgrounds prior to this is via a concept "demonstrator" detector prototype in drainage gallery
  - *We installed a 1/100 scale such device about 1 year ago*

Demonstrator Design



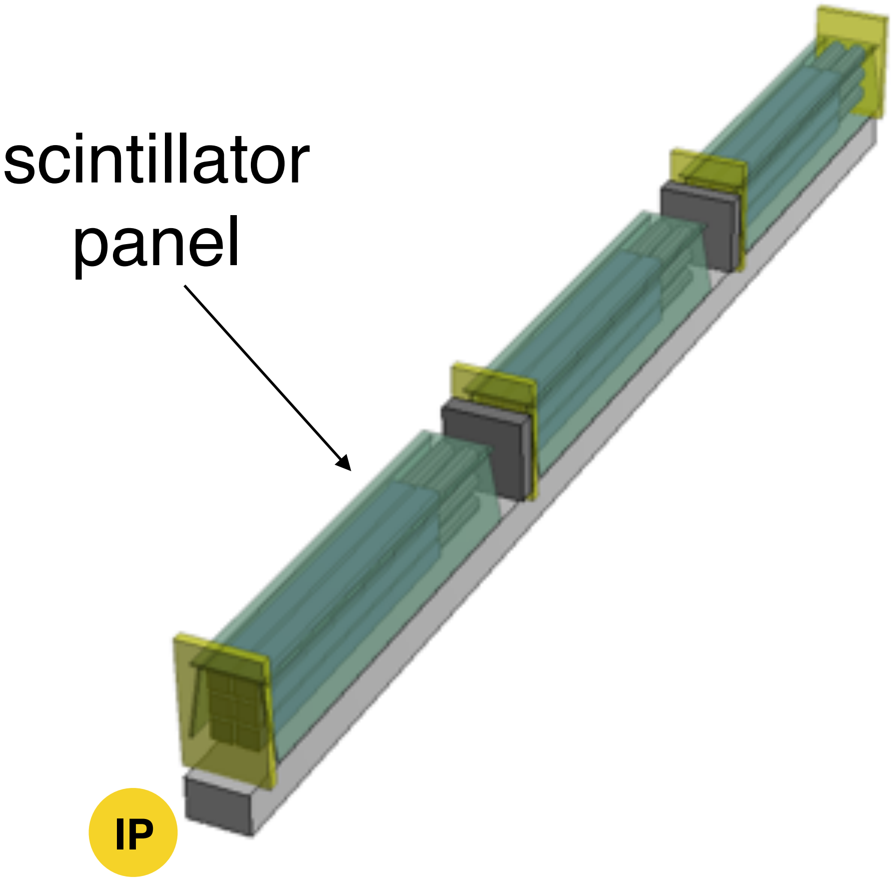
- In order to verify the feasibility and optimize the design of the experiment thoroughly, ~1% of the detector is installed as a "demonstrator"
- 3 layers of 2x3 scintillator+PMT

Demonstrator Design



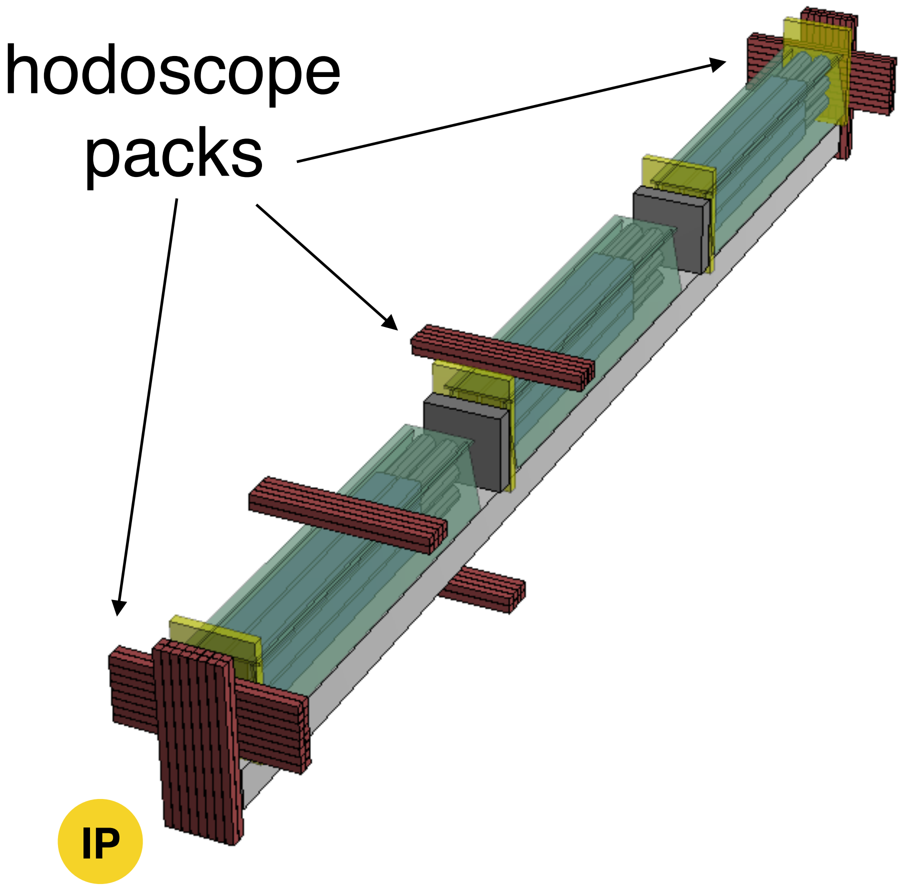
- In order to verify the feasibility and optimize the design of the experiment thoroughly, ~1% of the detector is installed as a “demonstrator”
- 3 layers of 2x3 scintillator+PMT
- Scintillator slabs and lead bricks
  - *Tag thru-going particles, shield radiation*

Demonstrator Design



- In order to verify the feasibility and optimize the design of the experiment thoroughly, ~1% of the detector is installed as a “demonstrator”
- 3 layers of 2x3 scintillator+PMT
- Scintillator slabs and lead bricks
    - *Tag thru-going particles, shield radiation*
- Scintillator panels to covering top and sides
    - *Tag/reject cosmic muons*

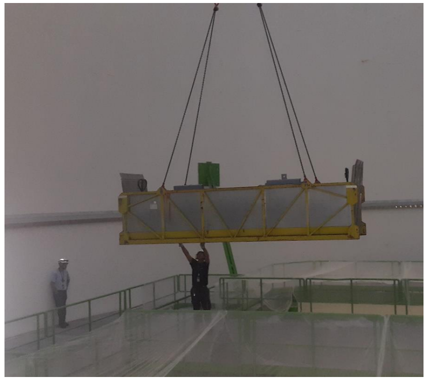
Demonstrator Design

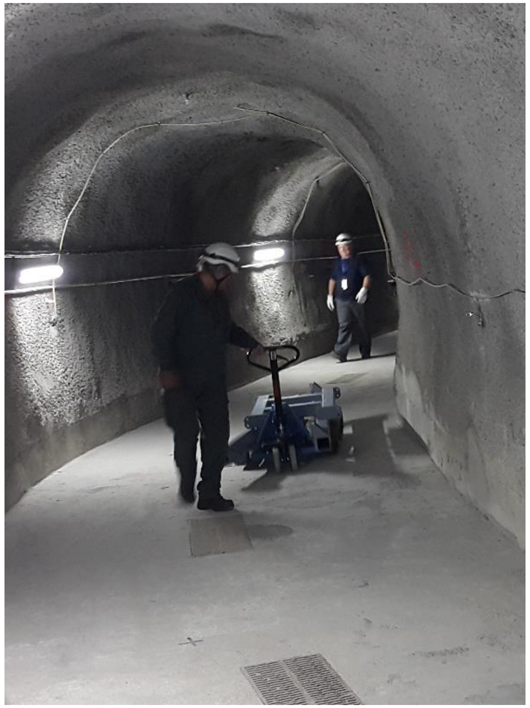


- In order to verify the feasibility and optimize the design of the experiment thoroughly, ~1% of the detector is installed as a “demonstrator”
- 3 layers of 2x3 scintillator+PMT
- Scintillator slabs and lead bricks
  - *Tag thru-going particles, shield radiation*
- Scintillator panels to covering top and sides
  - *Tag/reject cosmic muons*
- Hodoscope packs
  - *“Tracks” of beam/cosmic muons*

Mechanical Structure Deployed in TS1 of 2017





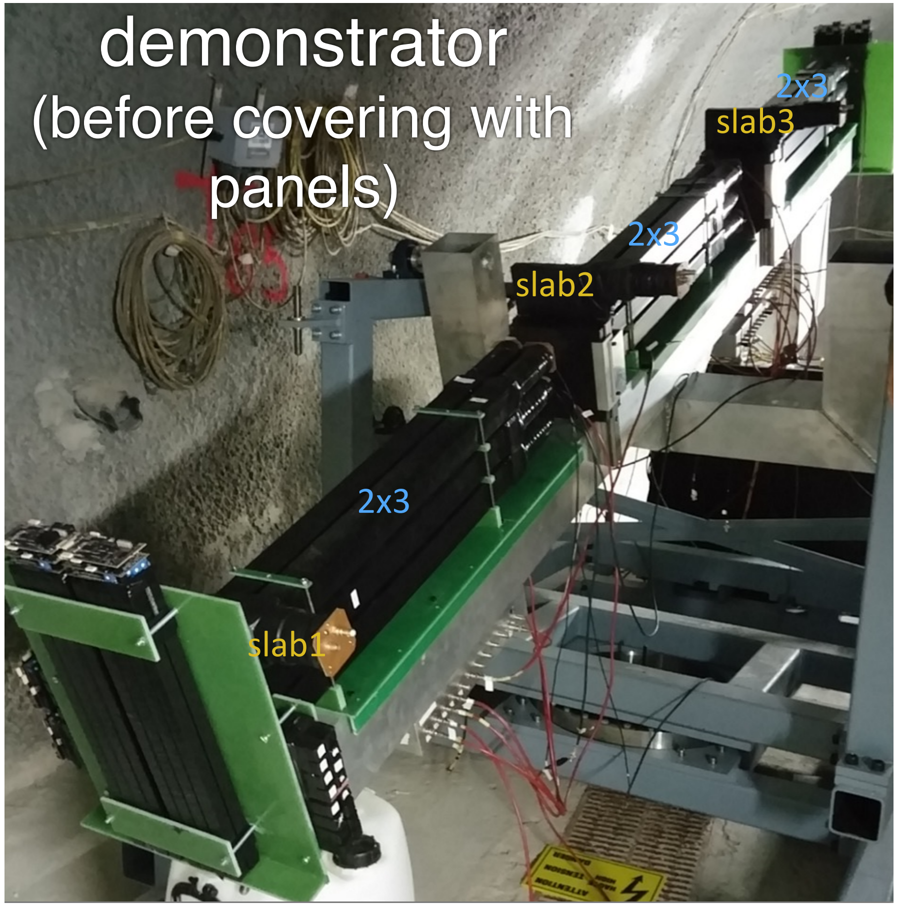



- Supports weight of “final” milliQan
- Rotates out of position to allow passage

Demonstrator Installed in TS2 of 2017

- Upgraded during 2017 YETS

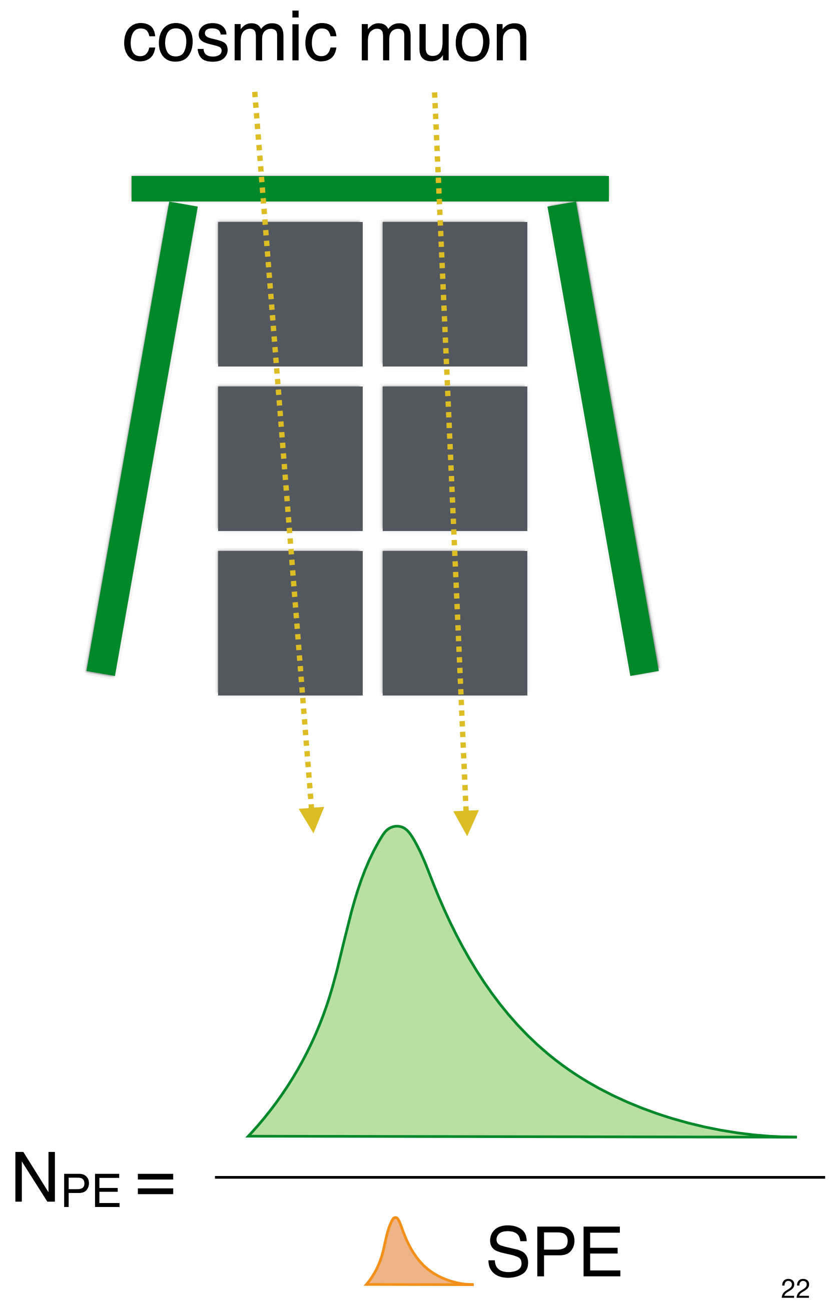
Installed demonstrator (before covering with panels)



- Been taking data ~continuously since then (during and between fills)

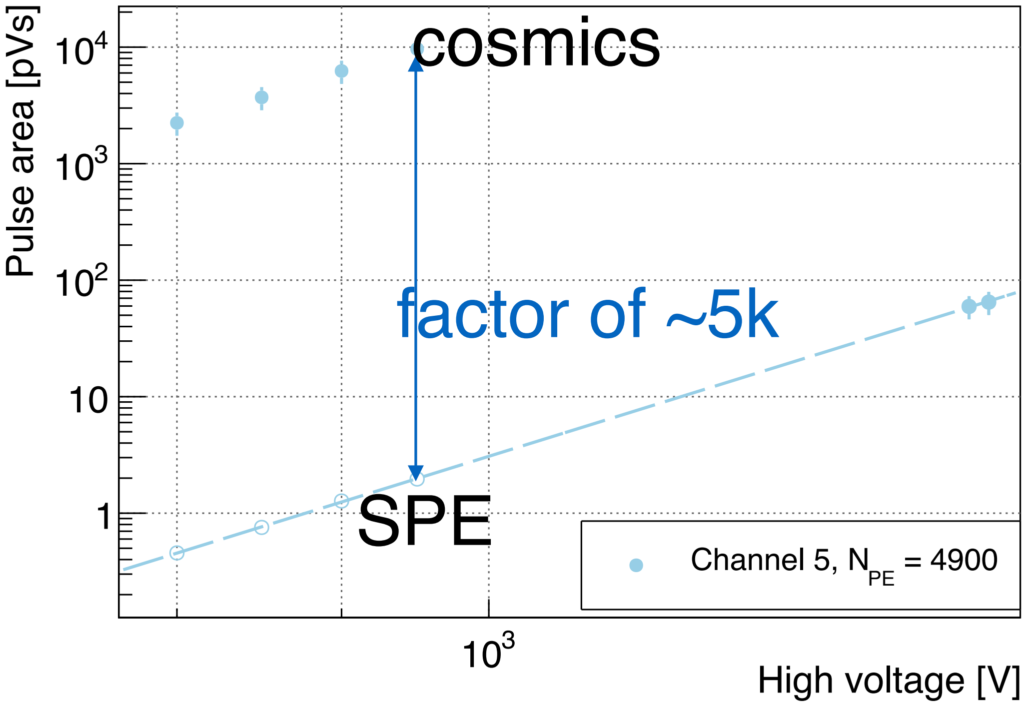
Demonstrator: *in situ* charge calibration

- 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) = Pulse area (cosmic muon) / Pulse area (SPE)*
- Extrapolate this to N_{PE} for fractional charges by Q^2



Demonstrator Results: *in situ* charge calibration

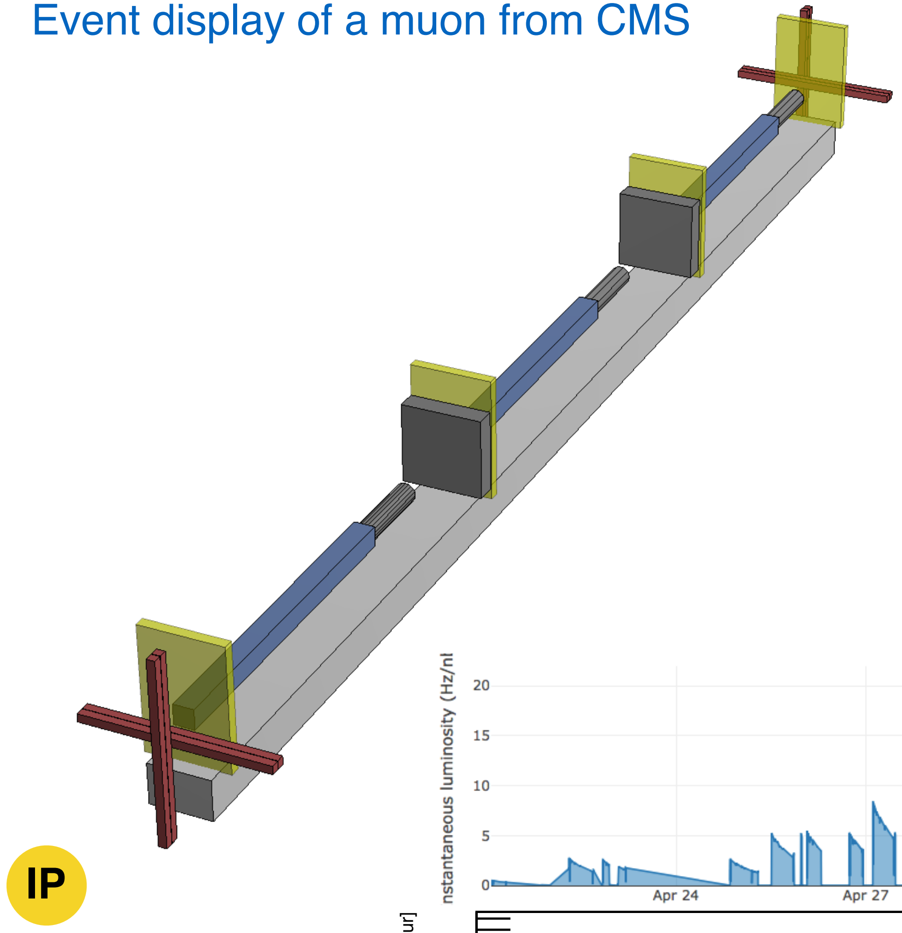
Pulse area as a function of HV for a PMT



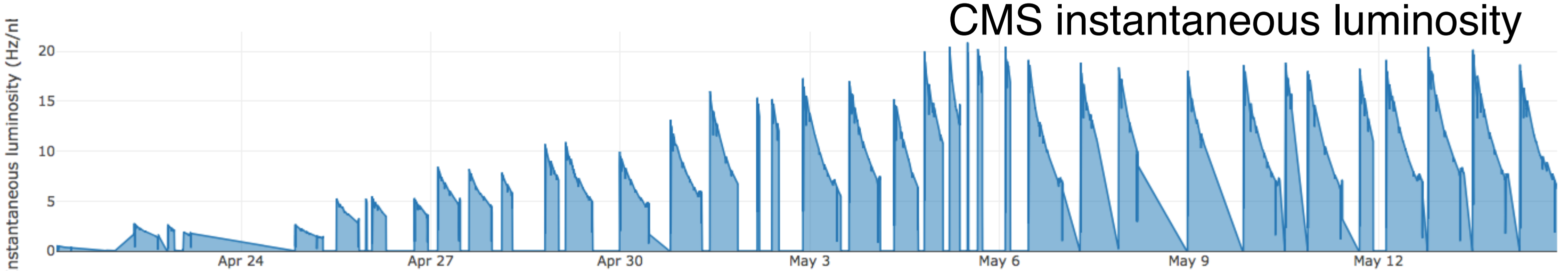
- N_{PE} for Q=1e is ~5k
- Flight distance of cosmic muons in scintillator is 5 cm
- For through-going muons, the flight distance is 80 cm
- N_{PE} for thru-going muon is 5k x 80/5 = 80k
- Since N_{PE} is proportional to Q^2
  - *N_{PE} = 1 for Q ~ 0.003e*
- Consistent with full Geant4 simulation results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

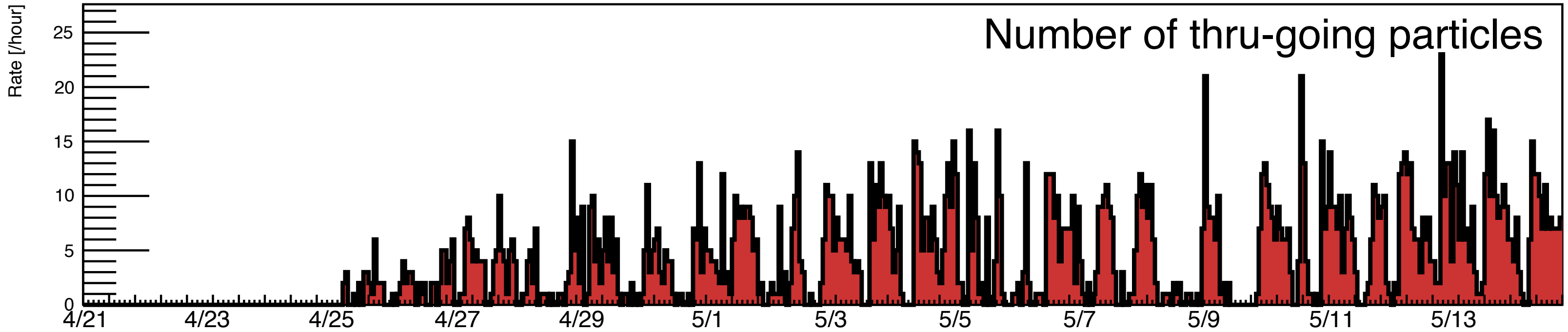
Demonstrator: *muons from CMS*

Event display of a muon from CMS



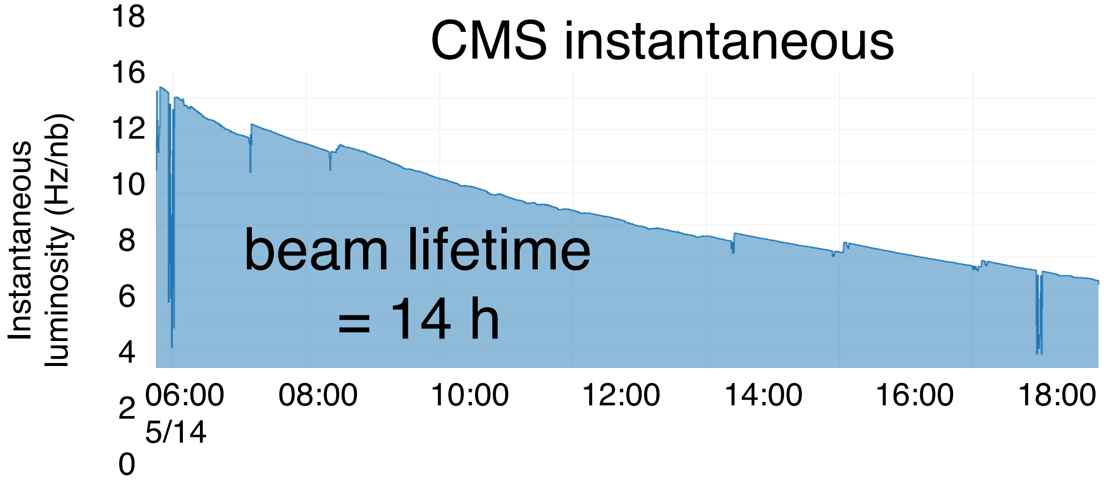
- Use the demonstrator to study muons from pp collisions in CMS
  - *Select thru-going particles*
  - *Useful for alignment, triggering, timing calibration, etc*

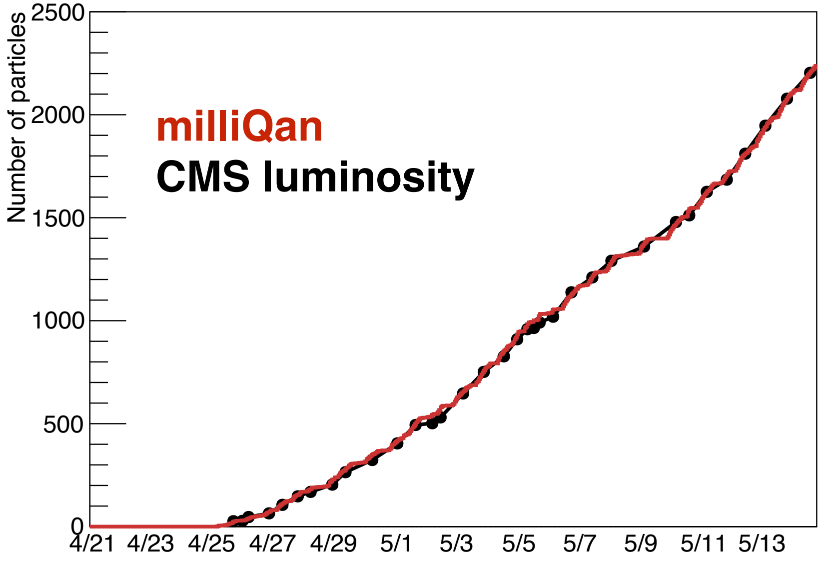

CMS instantaneous luminosity

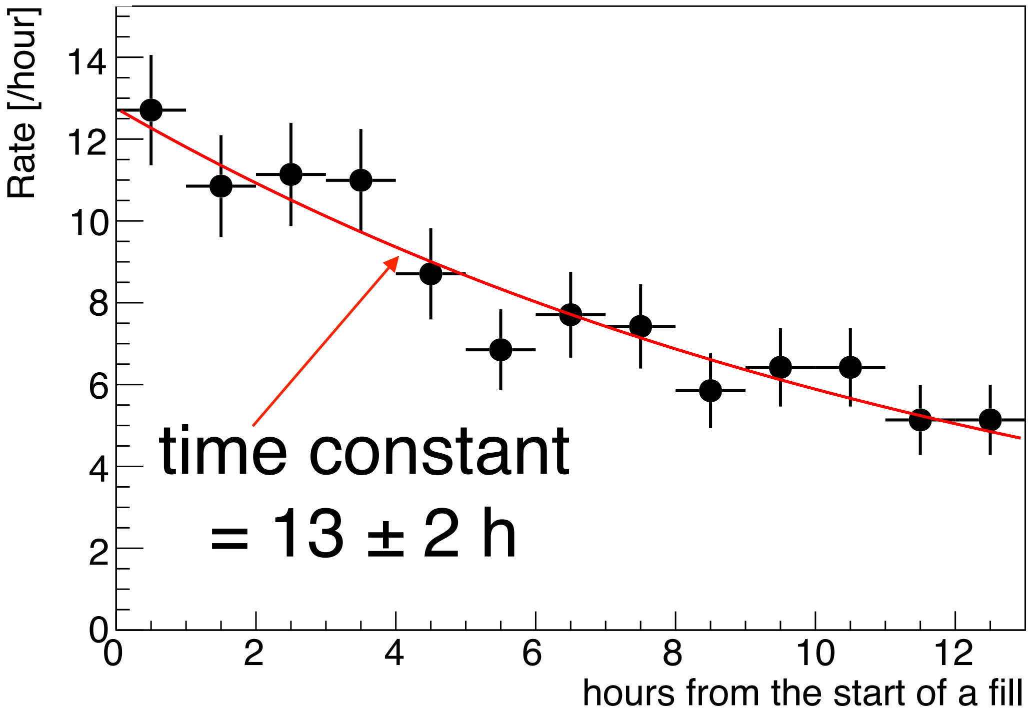

Number of thru-going particles

Demonstrator Results: *muons from CMS*

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

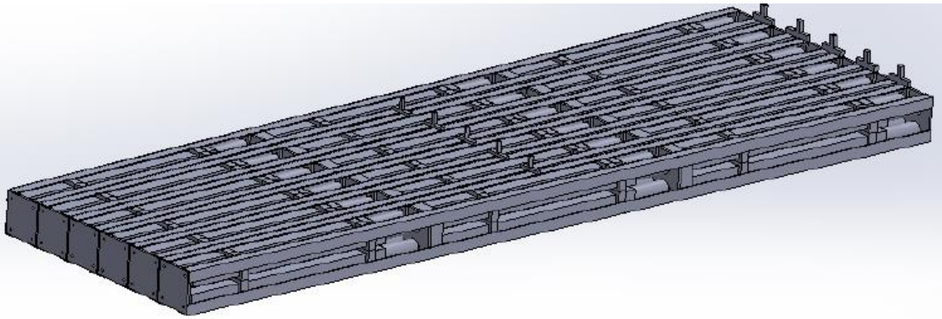


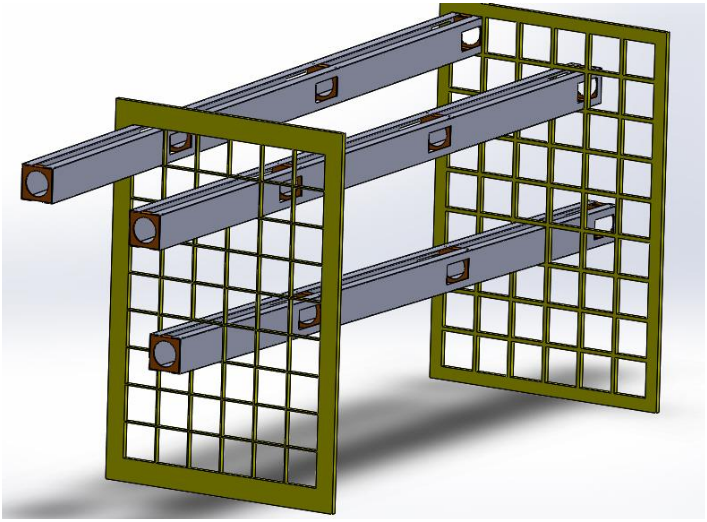


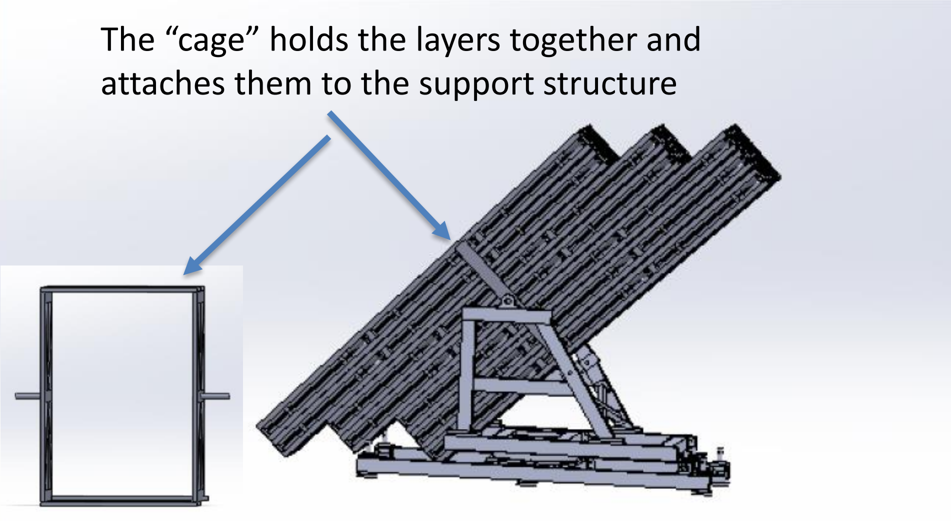


Advanced Design for Mechanical Supports for Modules

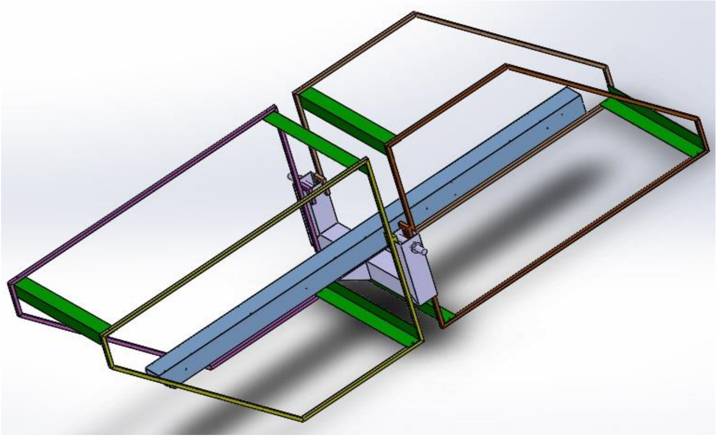
- The layer
- The steps

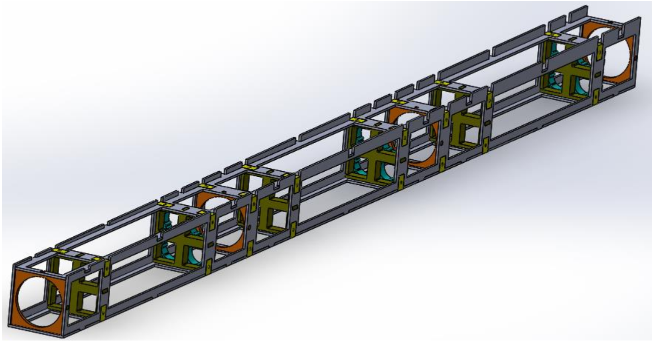


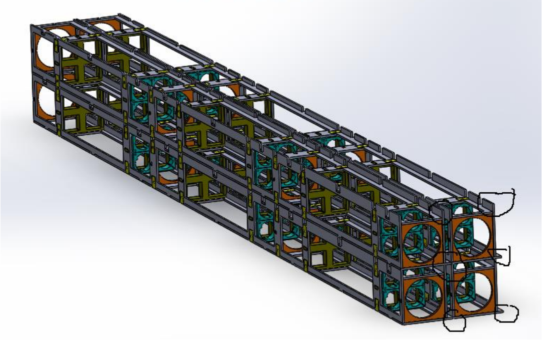


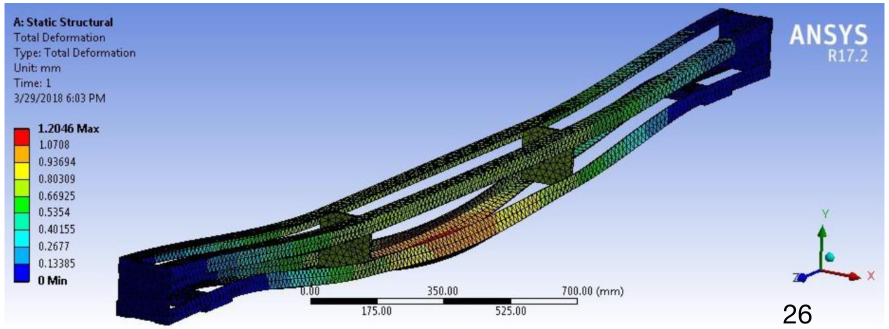


The “cage” holds the layers together and attaches them to the support structure









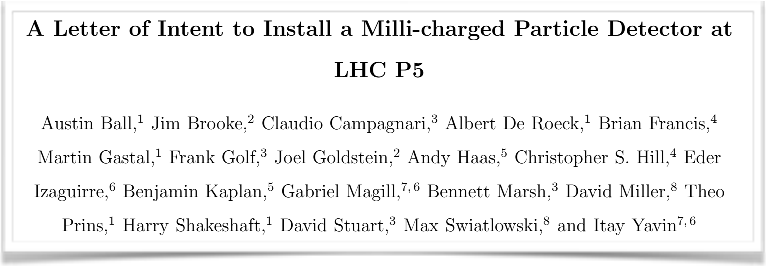
milliQan Collaboration

- **~20 people, 12 institutes, 6 countries**
- 9 “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**)*
    - *Karlsruhe Institute of Technology (**R. Ulrich**)*
    - *Lebanese University (**H. Zaraket**)*
    - *University of Virginia (C. Neu)*
    - *FNAL (J. Hirschauer)*
- 2 “ATLAS” groups
    - *New York University (**A. Haas***, B. Kaplan)*
    - *University of Chicago (**D. Miller,** M. Swiatlowski)*
- 2 “Theory” groups
    - *Perimeter Institute/McMaster Univ. (G. Magill)*
    - *Brookhaven National Lab (**E. Izaguirre**)*

*denotes co-spokepersons

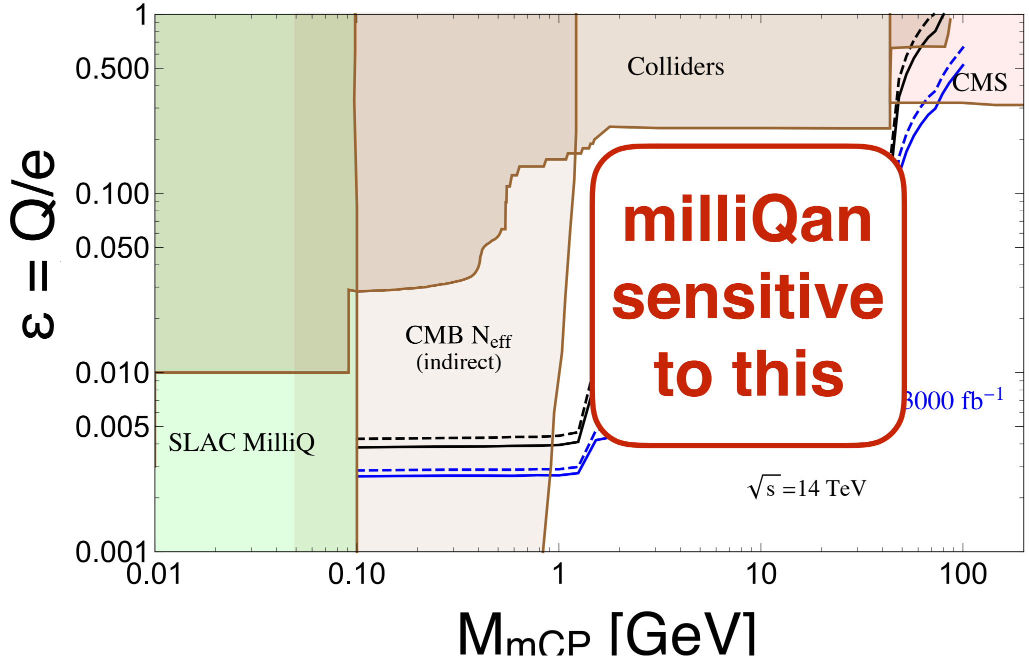
3rd milliQan collaboration meeting, Nov. 2017

Summary & Next Steps



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]

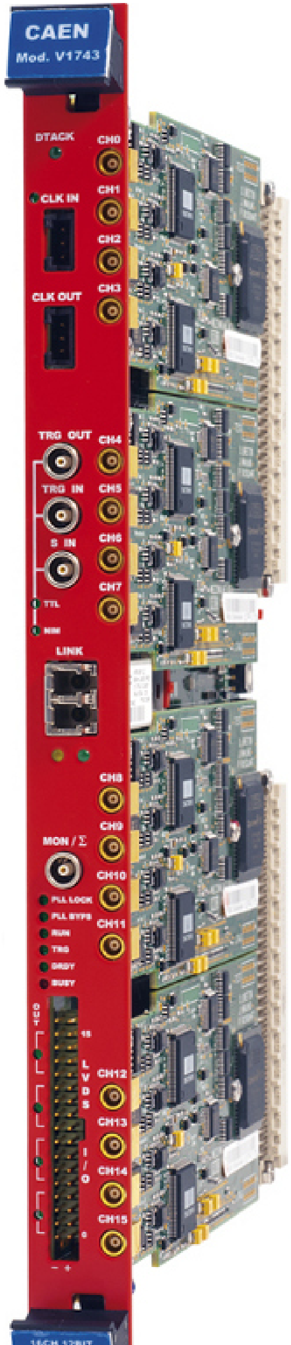


milliQan sensitive to this

- **milliQan** is a proposed experiment sited in a in a vestigial drainage gallery that will detect **millicharged particles** produced by pp collisions by CMS
- Unique sensitivity to unexplored 1-100 GeV and Q<0.3e region
- 1% demonstrator installed last year; being used to validate design and measure backgrounds
    - *Learning a lot about background and gaining experience in detector operation*
    - *Demonstrator data might provide first sensitivity to the uncovered region*
- If funding arrives in time, hope to install full-scale experiment **during LS2; run for Run 3 and beyond!**

Additional Material

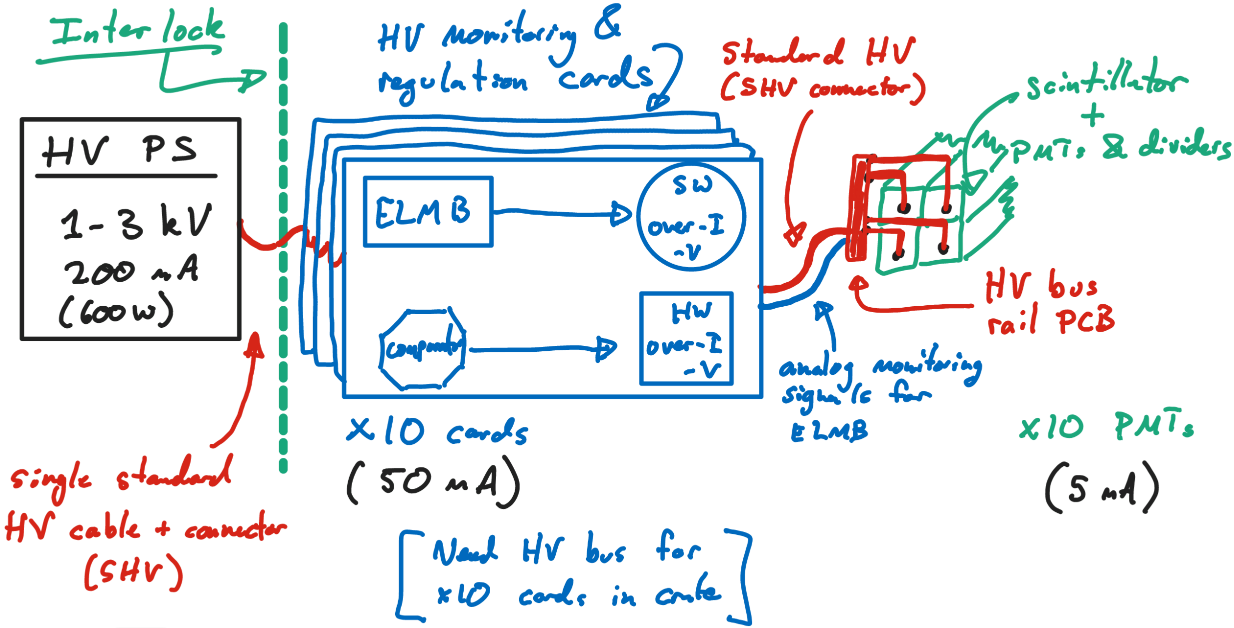
Basics of Readout & Trigger

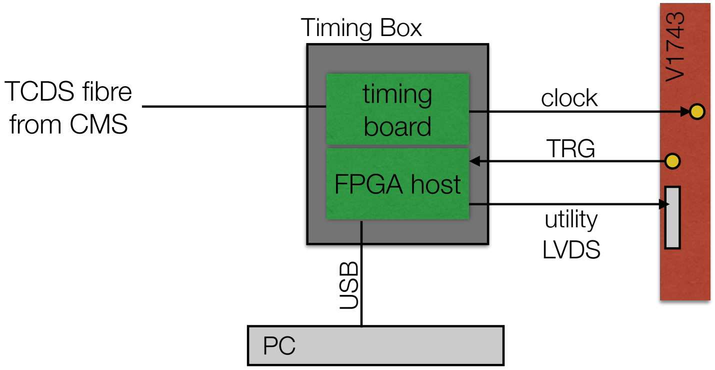


- Readout via CAEN V1743 12 bit digitizer
- 16 channels
  - *Sampled at 3.2 GS/s (a sample each 312.5 ps)*
  - *1024 analog buffer ring (320 ns long).*
  - *Analog noise is about 0.75 mV per channel, allowing good identification of and triggering on single PE signals*
- Trigger
  - *If 2 of 3 bars coincident 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**

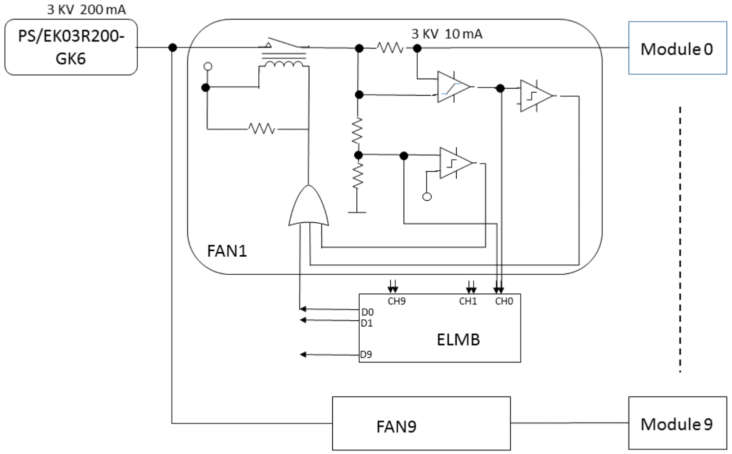
Powering, Slow Controls, Monitoring, Timing

- 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)*



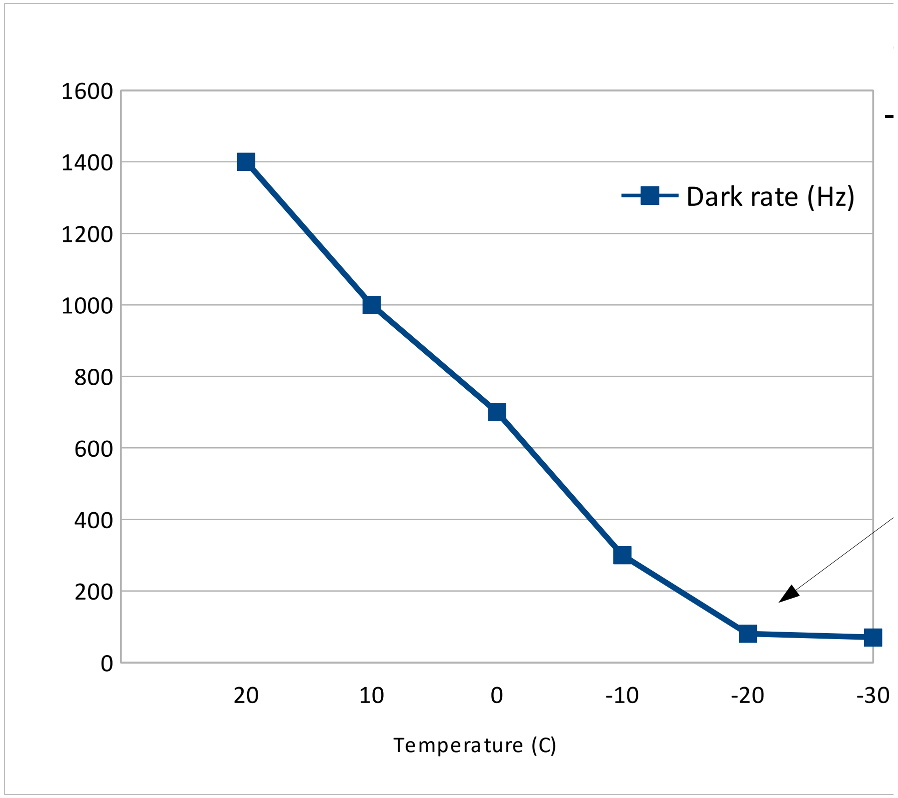


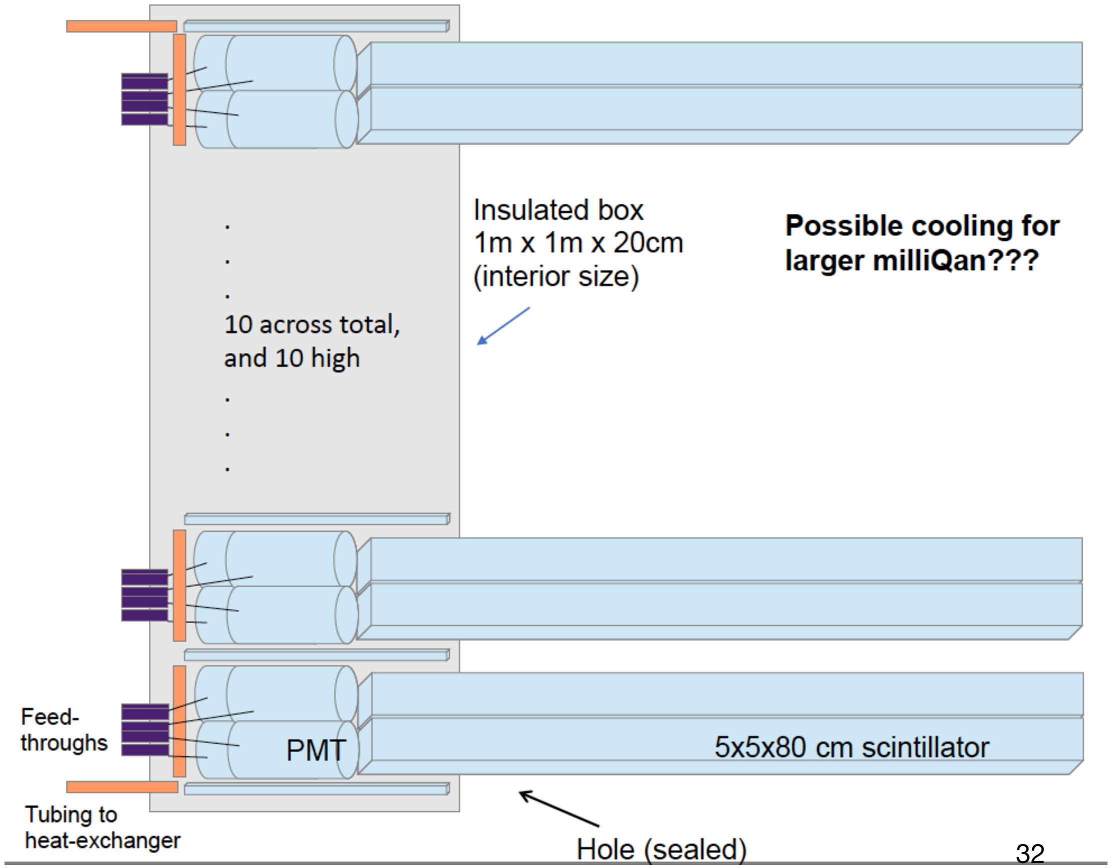
- Timing box receives TCDS fibre from CMS
- Recover LHC clock and send to V1743
- Decode CMS run/lumi/orbit signals
- Receive trigger from V1743, and readout data to PC



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**

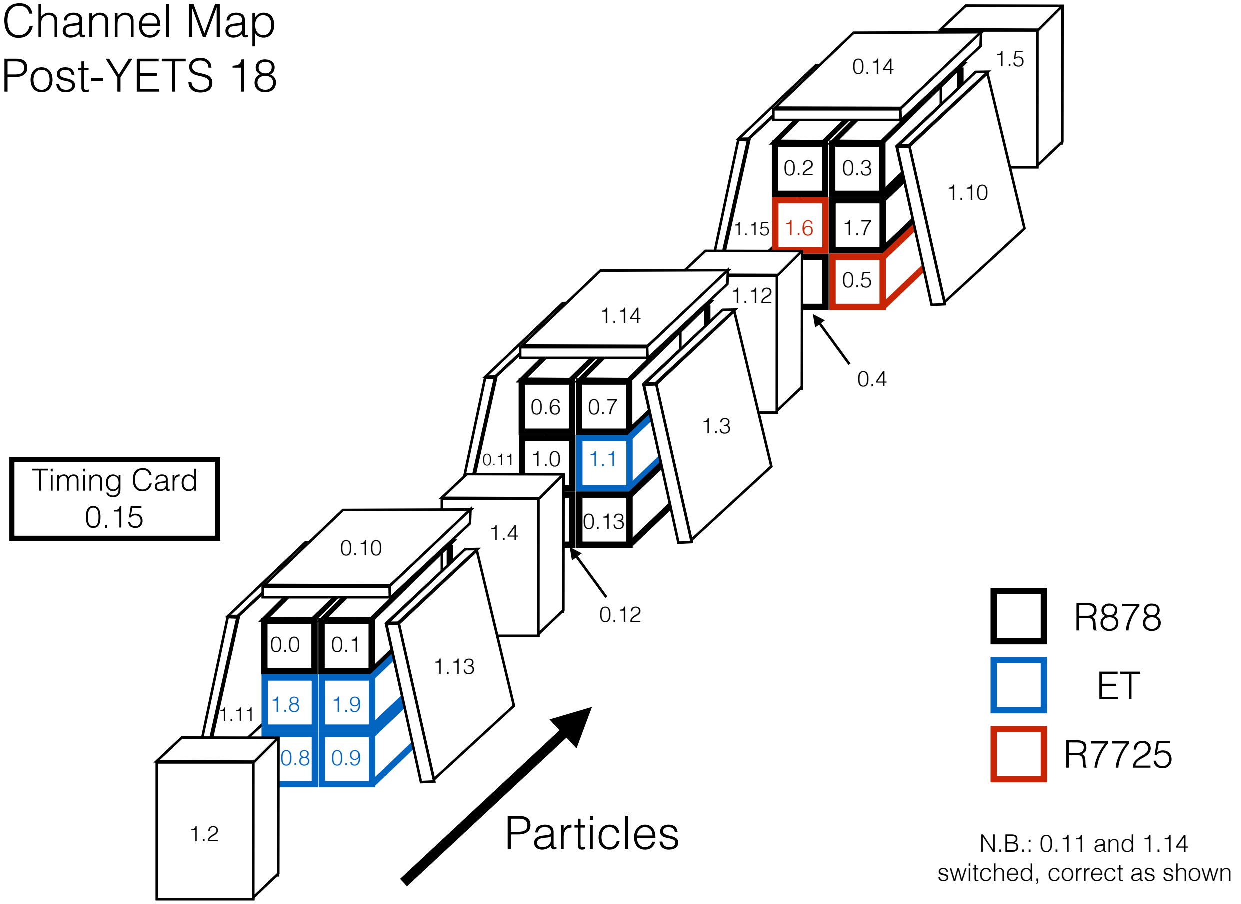




Demonstrator Upgraded during 2017-18 YETS

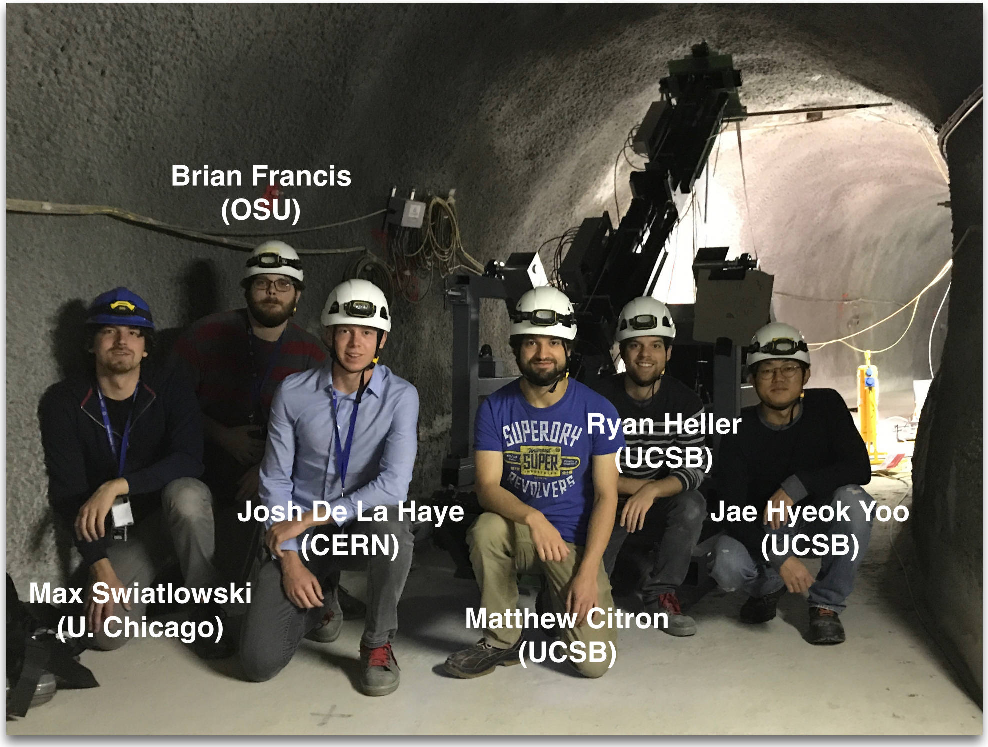
- Now have 18 milliQan bars
- 9 thin scintillator veto sheets
- 4 scintillator slabs between bars
- Expanded hodoscope
- Timing information from CMS
- 4 magnetic field sensors
- Temperature & humidity sensors
- Fire protection system

Channel Map
Post-YETS 18



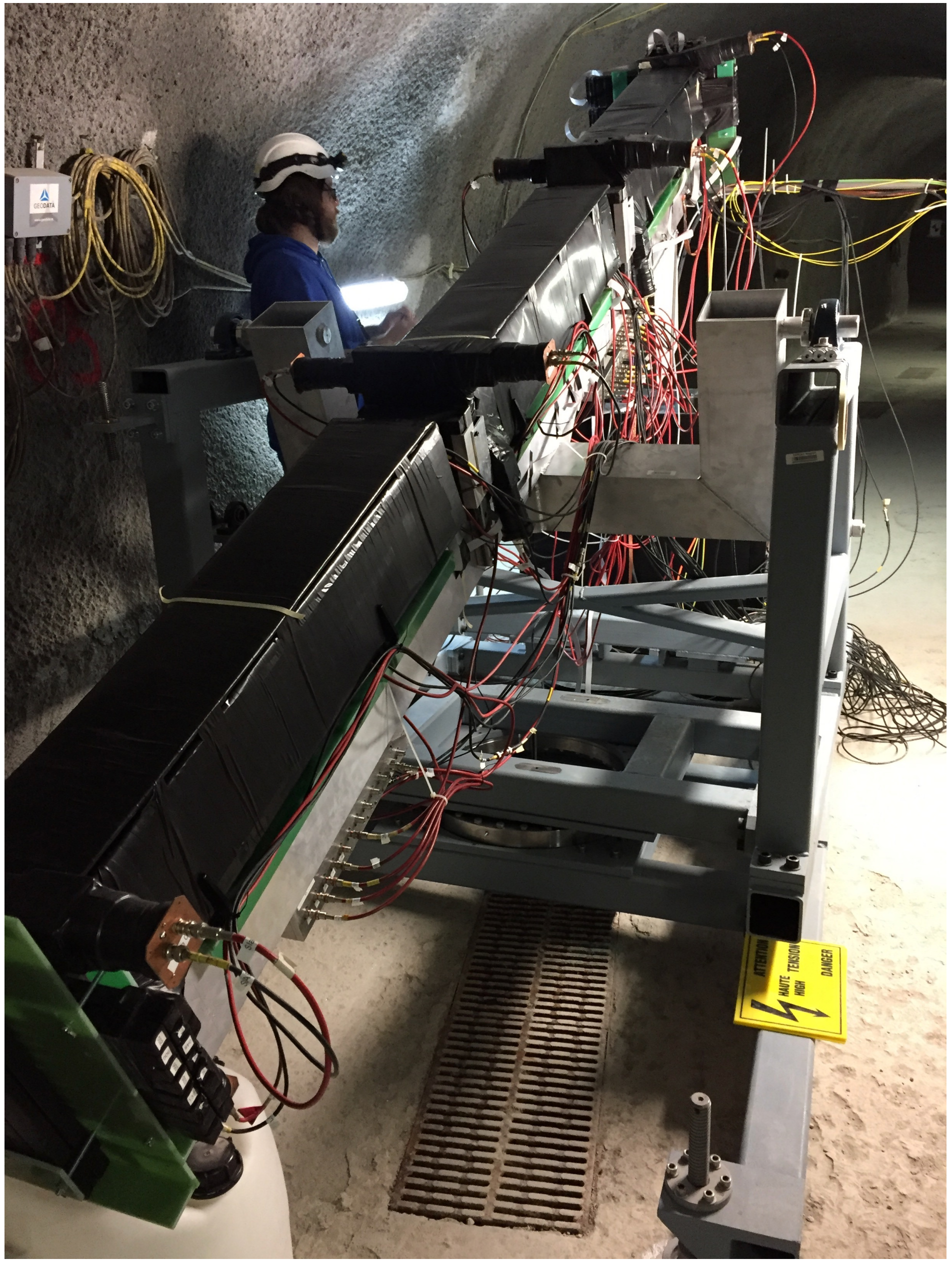
N.B.: 0.11 and 1.14 switched, correct as shown

Installation of demonstrator



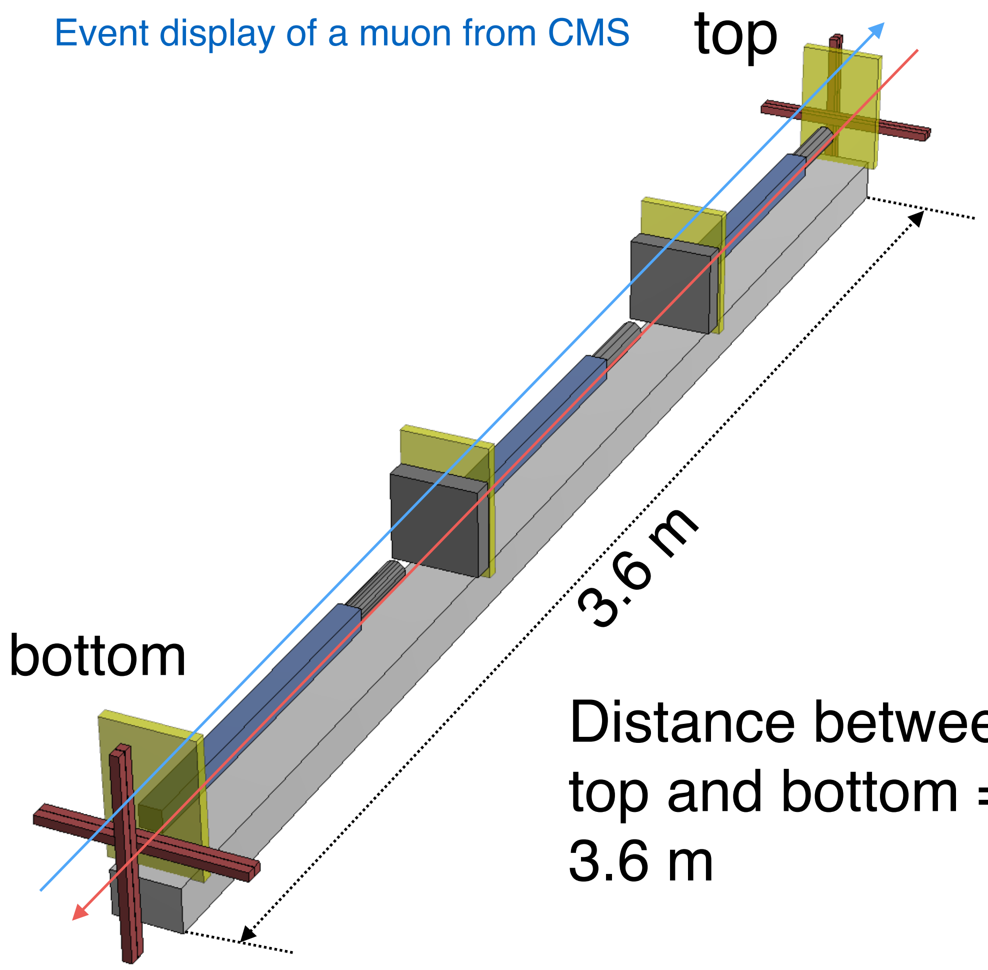
Installation team in front of the demonstrator

Demonstrator Upgraded during 2017-18 YETS

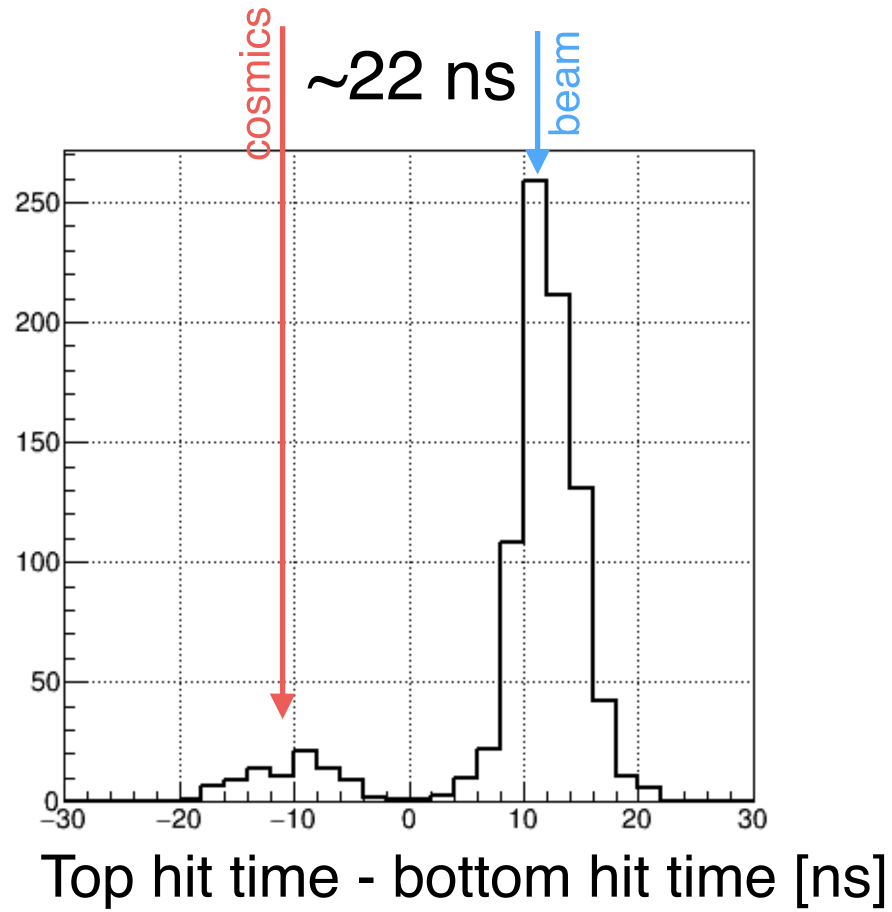


- Added additional set of milliQan bars in vertical dimension to aid with cosmic identification
- Added thin sheets on scintillator on top and side to aid in cosmic veto
- Added scintillator slabs between between bars to help understand longitudinal “showers”
- Added some environmental sensors to help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

Demonstrator: timing of thru-going particles

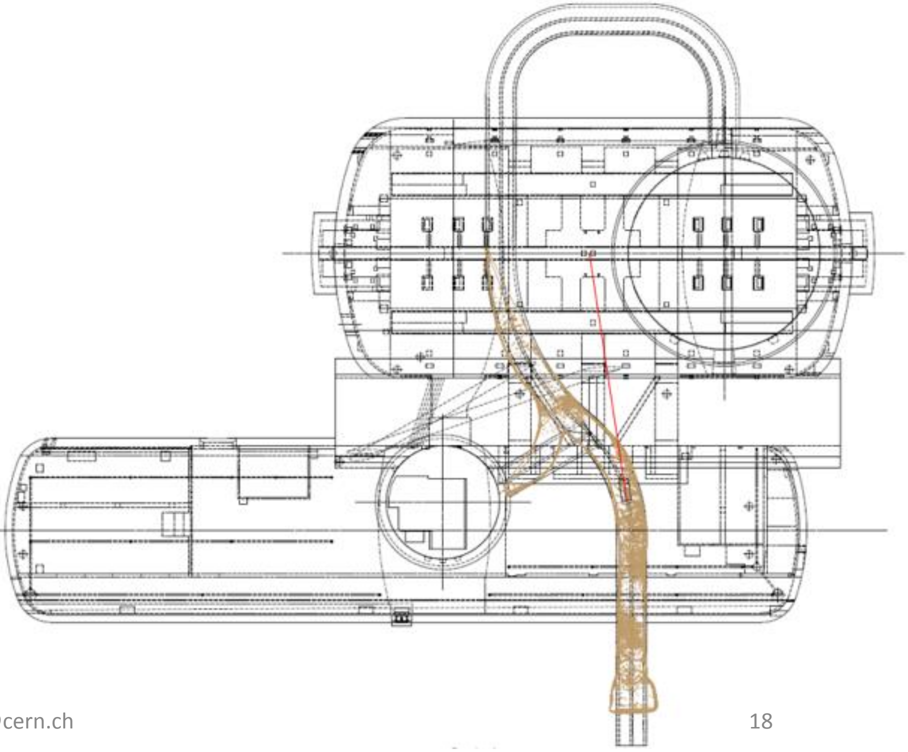

Event display of a muon from CMS

Distance between top and bottom = 3.6 m

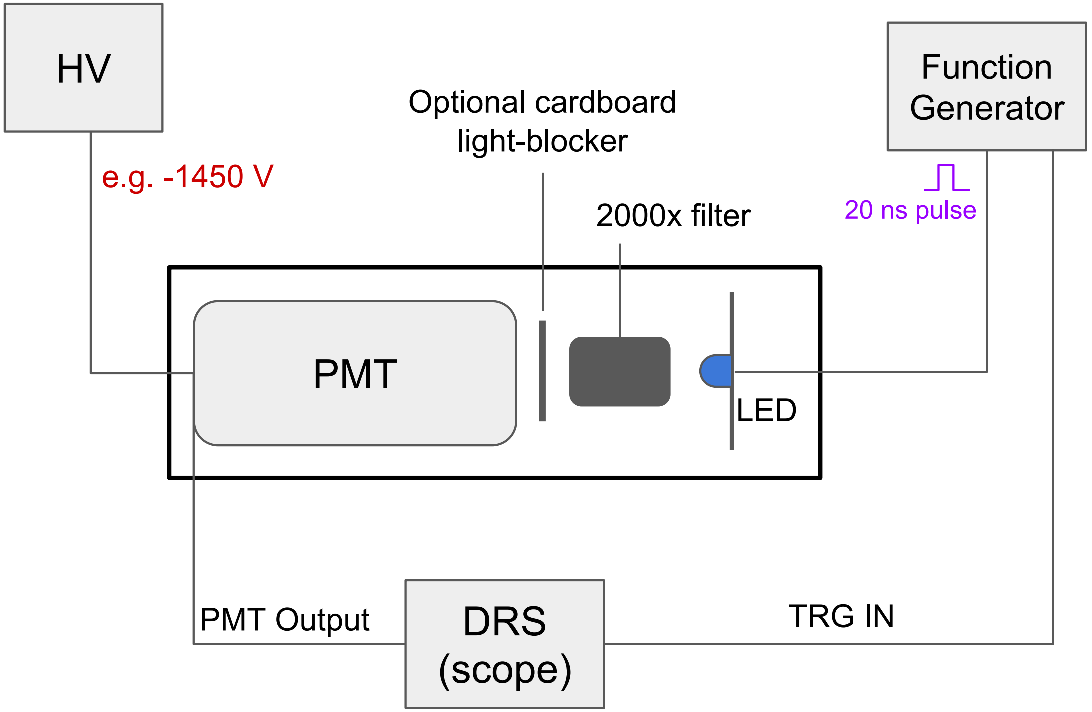


Alignment of demonstrator

- 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


HV

e.g. -1450 V

Optional cardboard light-blocker

2000x filter

Function Generator

20 ns pulse

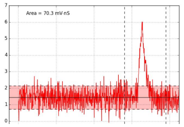
PMT

LED

PMT Output

DRS (scope)

TRG IN



Can control $\langle N_{PE} \rangle$ by varying amplitude of input LED pulse

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

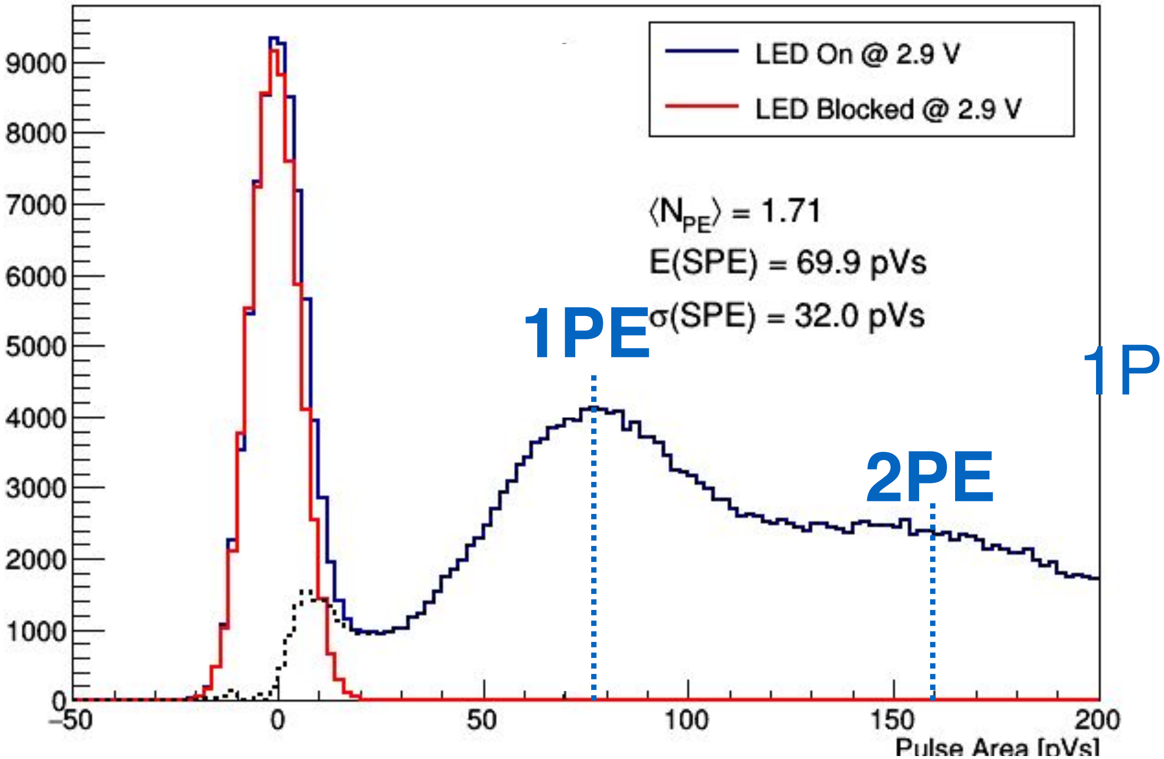
No need for any peak-finding, and allows us to trigger on “blank” (0-PE) events

LED:
Thorlabs LED430L
430 nm (blue/violet)

PMTs:
Hamamatsu R878
Hamamatsu R7725

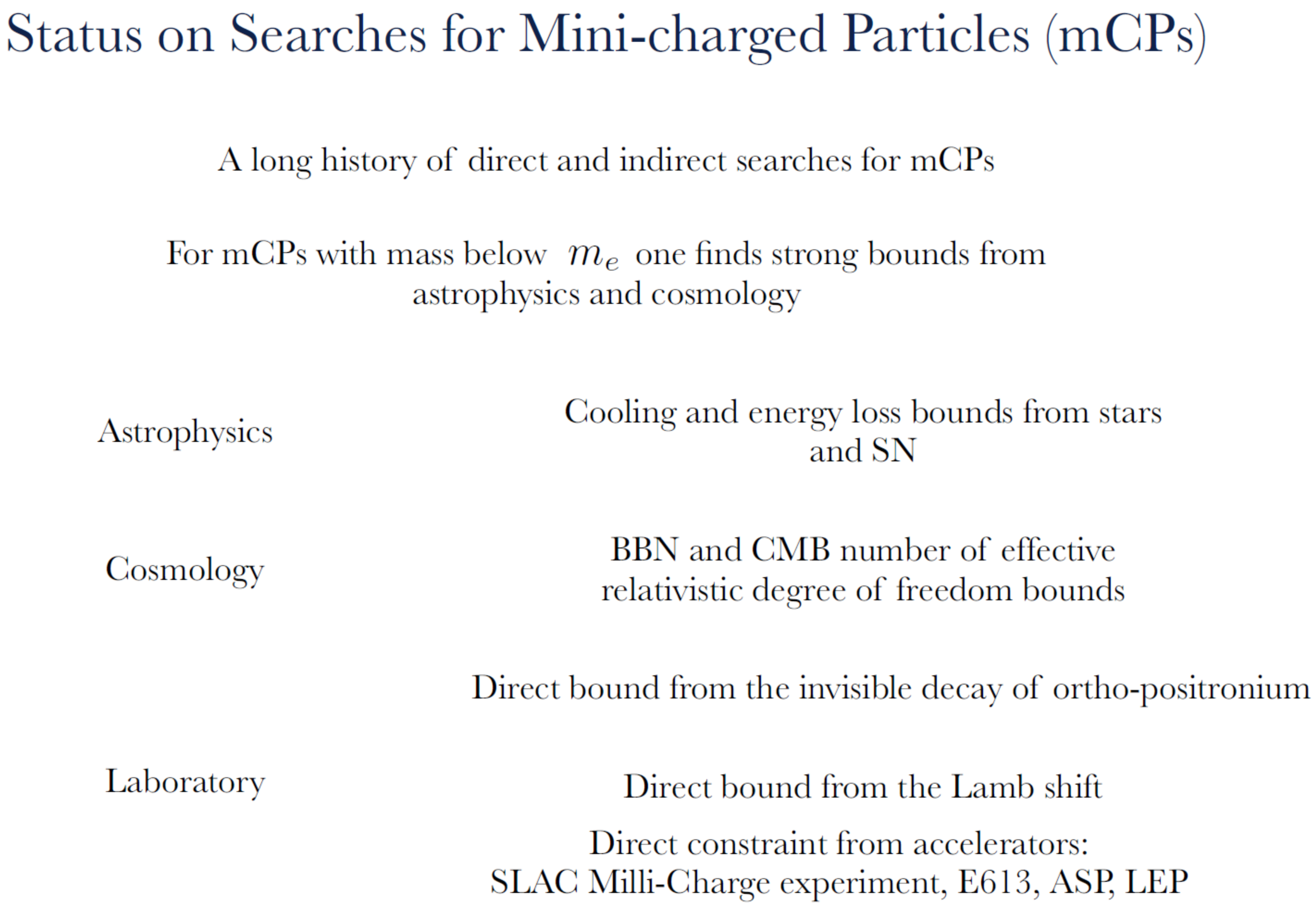
Charge calibration: bench results

R878 @ 1450V



1PE peak at 80 pVs

History of millicharged particle searches



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

Astrophysics	Cooling and energy loss bounds from stars and SN
Cosmology	BBN and CMB number of effective relativistic degree of freedom bounds
Laboratory	Direct bound from the invisible decay of ortho-positronium Direct bound from the Lamb shift Direct constraint from accelerators: SLAC Milli-Charge experiment, E613, ASP, LEP

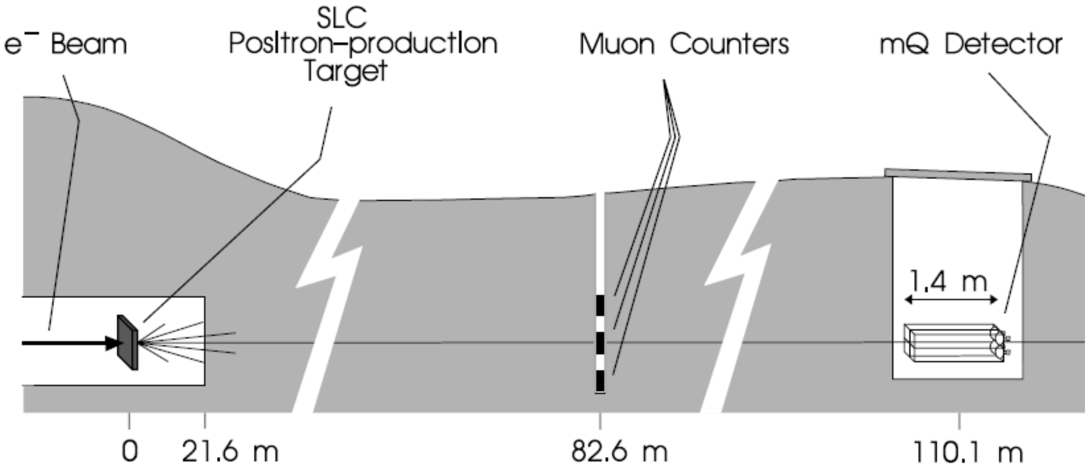
SLAC MilliCharge Experiment

Phys.Rev.Lett. 81 (1998) 1175-1178

29.5 GeV pulsed electron beam

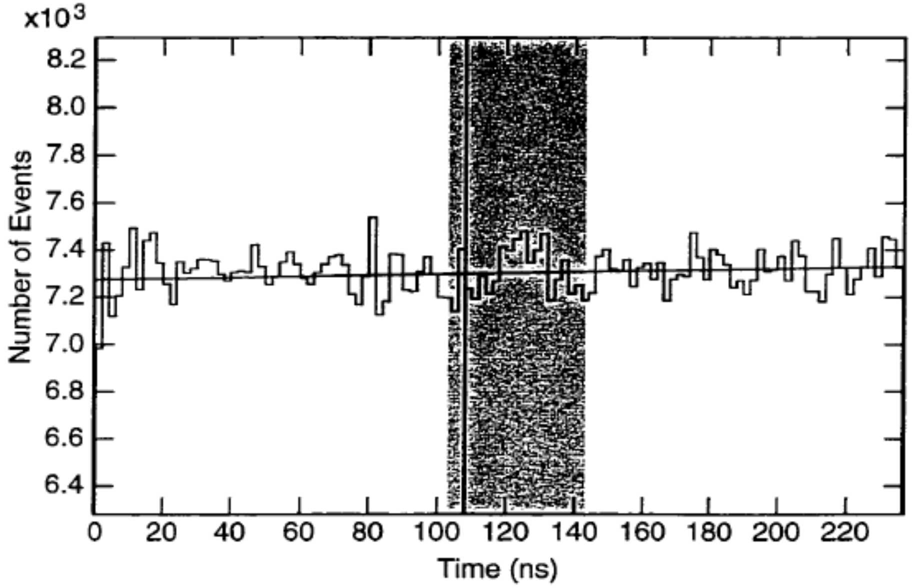
~ 10^{19} electrons on target

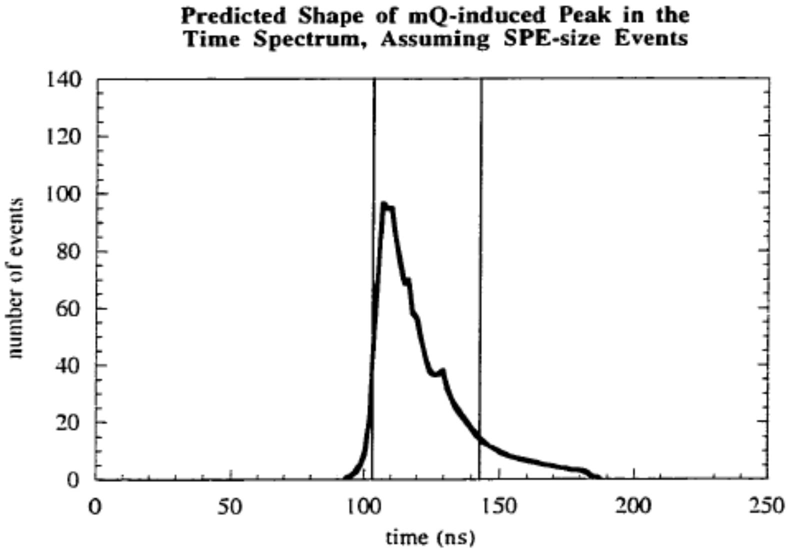
Good time resolution is essential, and tricky for small (SPE) pulses!



mQ detector

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

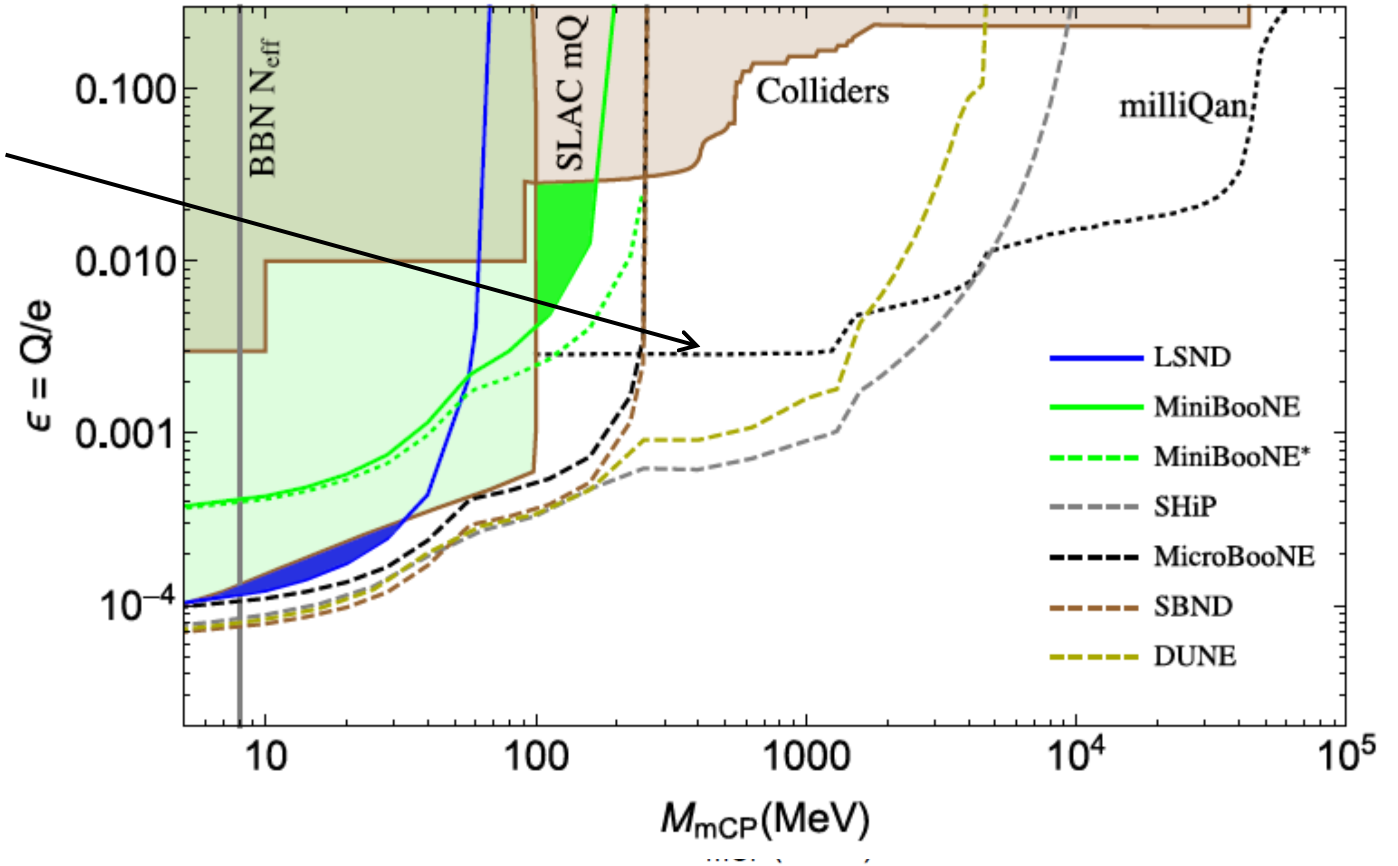



Predicted Shape of mQ-induced Peak in the Time Spectrum, Assuming SPE-size Events

Comparisons to Neutrino Experiments

95%CL Projected Sensitivities

This flattening is artificial, as we did not include the more complicated production of mCP from QCD/hadronic physics … (only DY and prompt resonances).

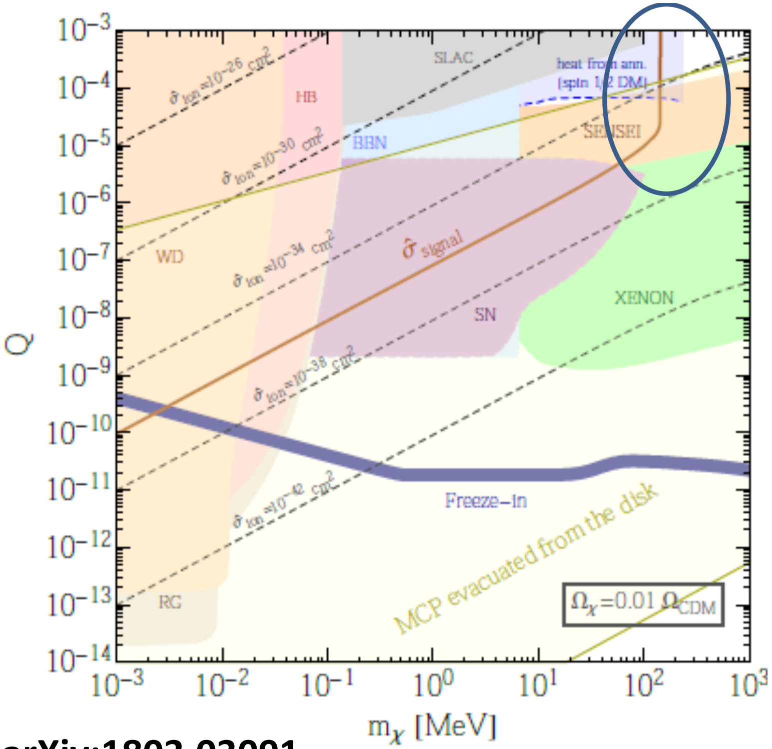


arXiv: 1806.03310 [hep-ph] 8 Jun 2018

Additional Physics Motivations

More Motivation?

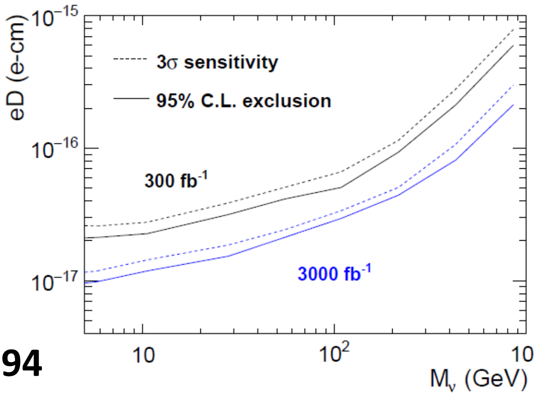
- Recent excitement that milli-charged dark matter at the 1% mass-density level is a leading explanation for the EDGES 21-cm result
- The mass/charge region favored is in a sweet-spot of milliQan sensitivity



arXiv:1803.03091

FIG. 4. Constraints on the charge, Q, of a millicharged particle as a function of the DM mass. The **red** line indicates the minimal cross section needed to explain the EDGES measurement, assuming the millicharged particle constitutes only 1% of the DM density. The **dashed-gray lines** show contours of constant $\hat{\sigma}$. Constraints from cooling of the supernova (SN) 1987A [6] (**purple**), direct detection limits from XENON10 [56, 63] (**green**) and SENSEI [74], SLAC millicharge experiment [22] (**gray**), BBN [7] (**light blue**) and cooling of white-dwarfs (WD), horizontal-branch (HB) stars and red-giants (RG) [8] (**pink and brown**) are shown in the shaded regions. We also add constraints from heating due to DM annihilation derived in [75] (**blue**). This bound only applies to fermionic DM for which the annihilation is *s*-wave. The shaded yellow band indicates where millicharged DM might be evacuated from the galactic disk [23, 29].

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



arXiv:1710.06894

FIG. 1: The expected 95% C.L. exclusion (solid) and 3σ sensitivity (dashed) for heavy neutrino EDM detection using the milliQan experimental setup at $\sqrt{s} = 14$ TeV, assuming $\mathcal{L} = 300$ (3000) fb^{-1} integrated luminosity in black (blue).