Status of and first data from the CMS **milliQan Run 3** "sub-detector(s)"

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on behalf of
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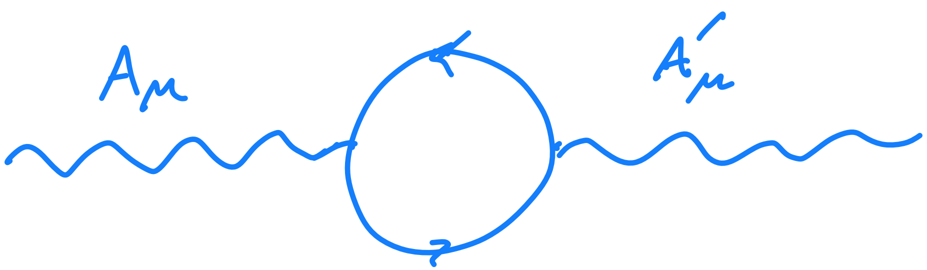
31st Lepton Photon Conference 2023
MELBOURNE CONVENTION & EXHIBITION CENTRE
17 - 21 JULY

What milliQan is …

Complementary **LHC hidden/dark sector experiment**

- Searches for dark sector particles inaccessible to ATLAS/CMS detectors, *but* with distinctive signature “*easily*” observable with “*simple*”, “*cheap*”, ancillary detector

If consider BSM extension with massless dark photon kinetically mixing with SM photon then any “dark” fermions will have fractional EM charge (after EWSB) — **Holdom PLB 196-198 (1986)**



mass of BSM fermion

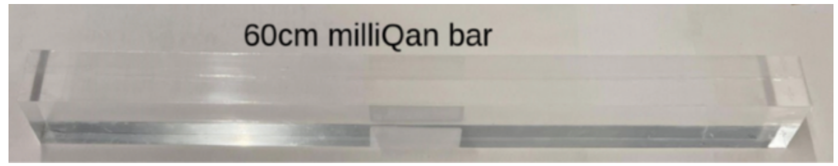
$$\mathcal{L} = \mathcal{L}_{SM} - \frac{1}{4}A'_{\nu\mu}A'^{\mu\nu} + i\bar{\psi}(\not{\partial} + ie'\not{A}' + -i\kappa e'\not{B} + iM_{mCP})\psi$$

→ effective EM charge:

$Q = \kappa e' \cos\theta_W$

How milliQan works — basic idea

- Want to be sensitive to dark fermions produced in LHC collisions with EM charges down to Q/e ~10^{-3}
    - *Generically call these millicharged particles or mCPs*
- For mCPs with Q/e ~10^{-3} dE/dx is 10^{-6} that of a MIP
    - *Need long, sensitive, active length to see signal, $\mathcal{O}(1)$ PE.*
- Long “bars” of scintillator (+ PMTs with custom amplification) in an array pointing back to CMS
- Use coincidence to control (otherwise dominant) random backgrounds



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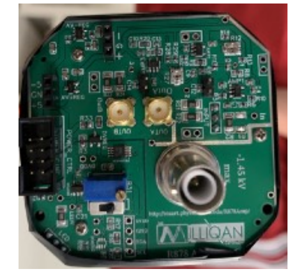
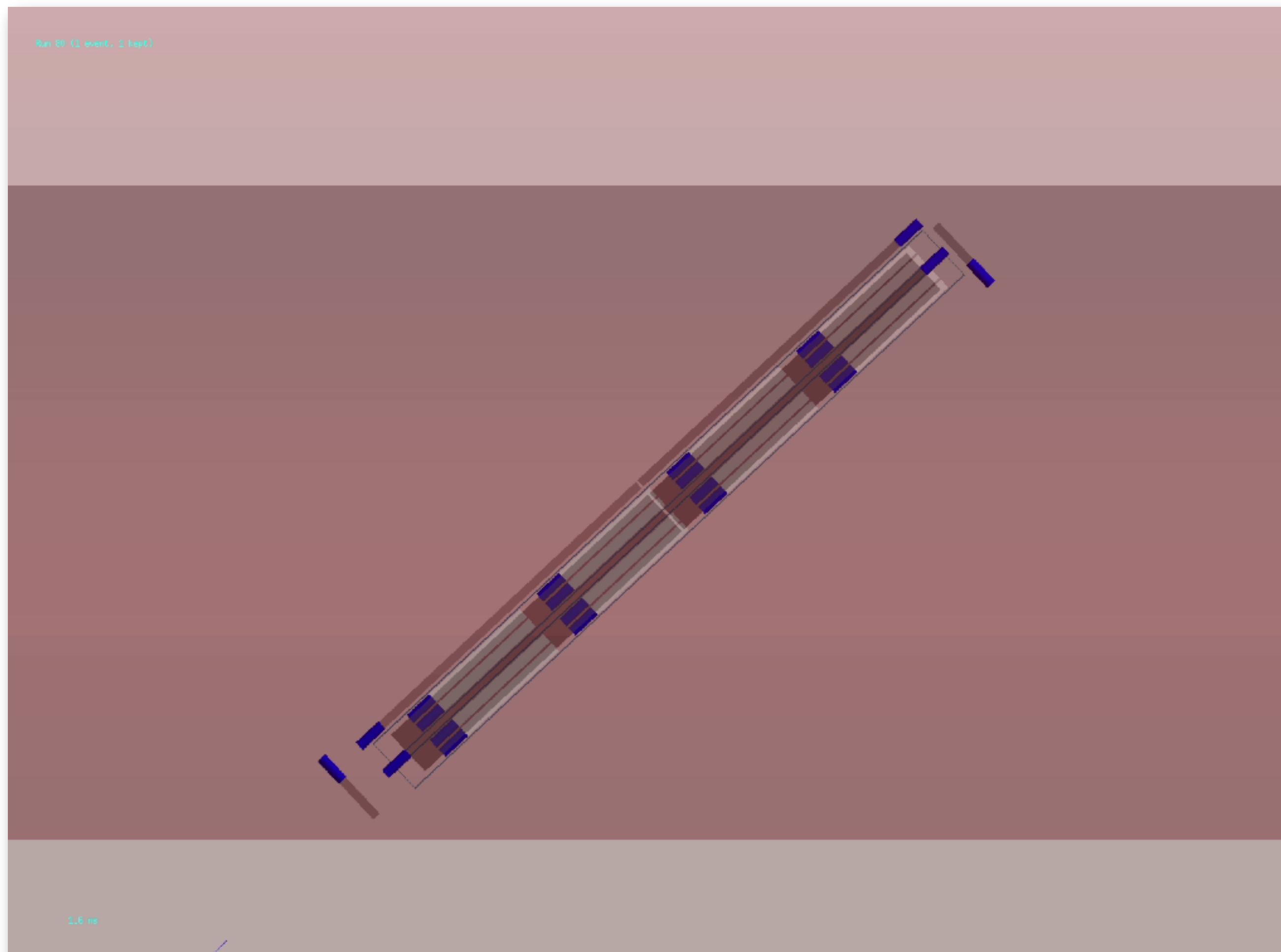
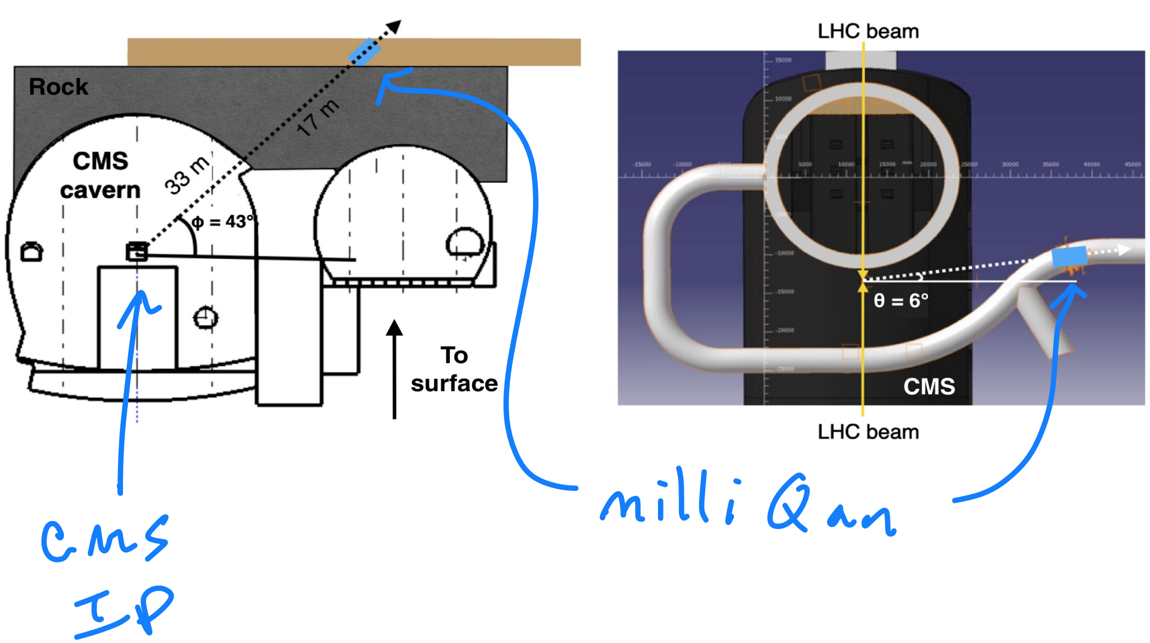
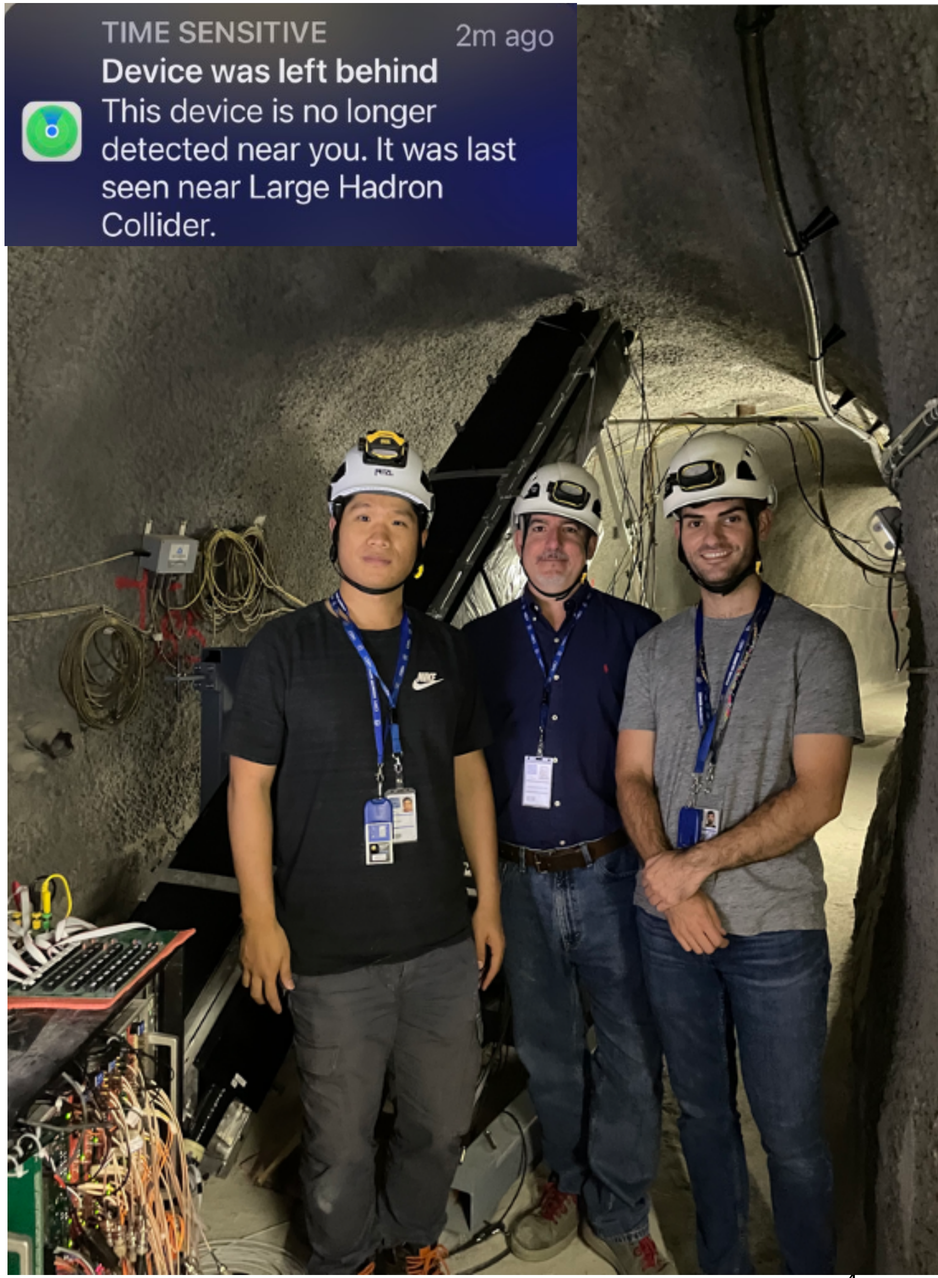




Where: milliQan in a tunnel above CMS

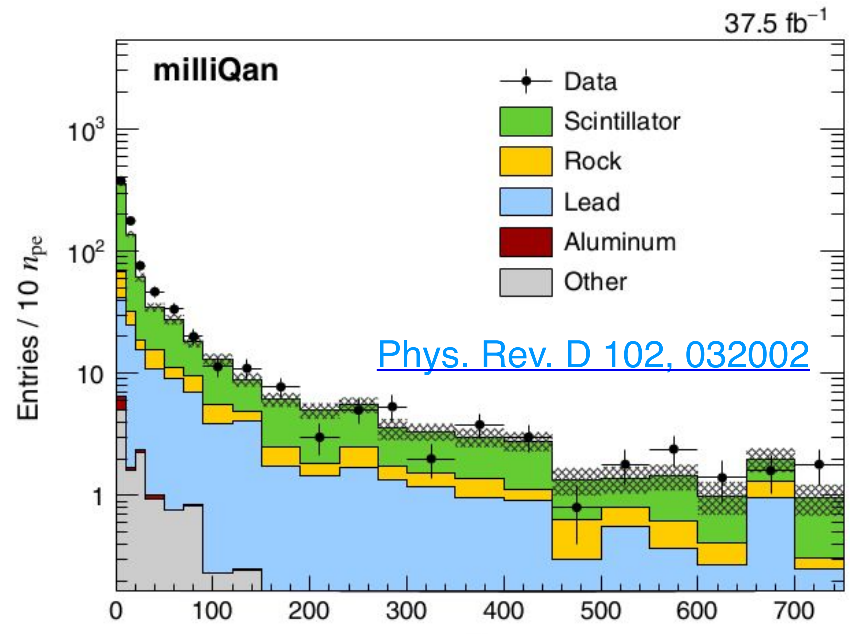
- At CERN, off-axis from LHC
    - *Detector in PX56 drainage gallery at P5 (above CMS)*
    - *33 m from CMS IP at an angle η≈0.1, ϕ≈43*
    - *17 m of rock act as natural shielding of beam particles*
    - *Cosmic muon flux suppressed by factor of 100 (compared to surface)*

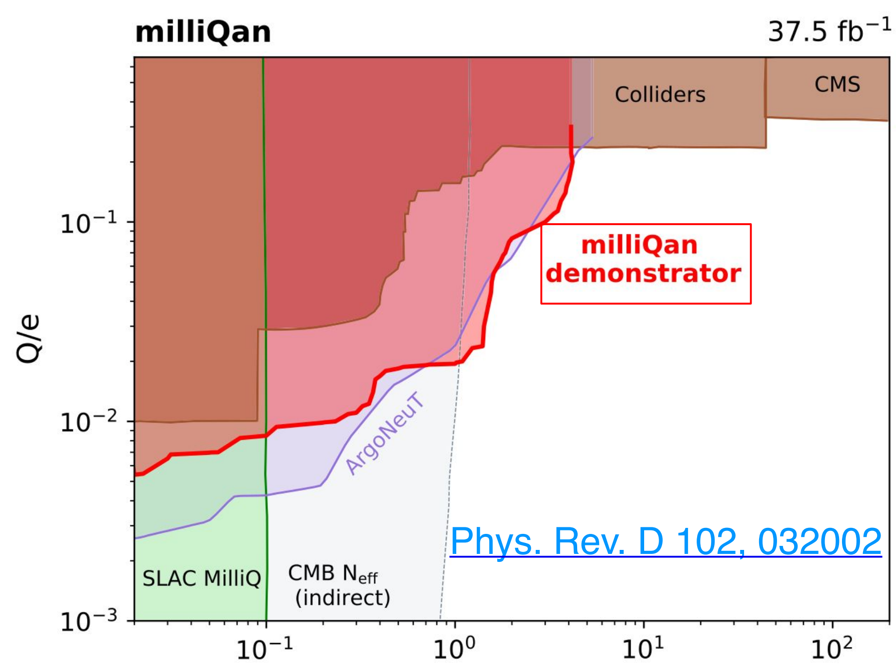




Proof of Principle: milliQan demonstrator

- Installed prototype detector for LHC Run 2 in PX56
    - *2x3 radial "layers" of 80 x 5 x 5 cm BC-408 scintillator bars pointing to CMS IP*
- Collected 37.5 fb^{-1} physics data
    - *>2000 h trigger live-time*
- Validated GEANT simulation and analysis techniques
- Learned invaluable lessons for Run 3
    - *Got lots of operating experience*
    - *Powerful resource to study/optimize performance of detector*
- Bonus: able to (just) extend constraints on mCP in charge vs. mass plane

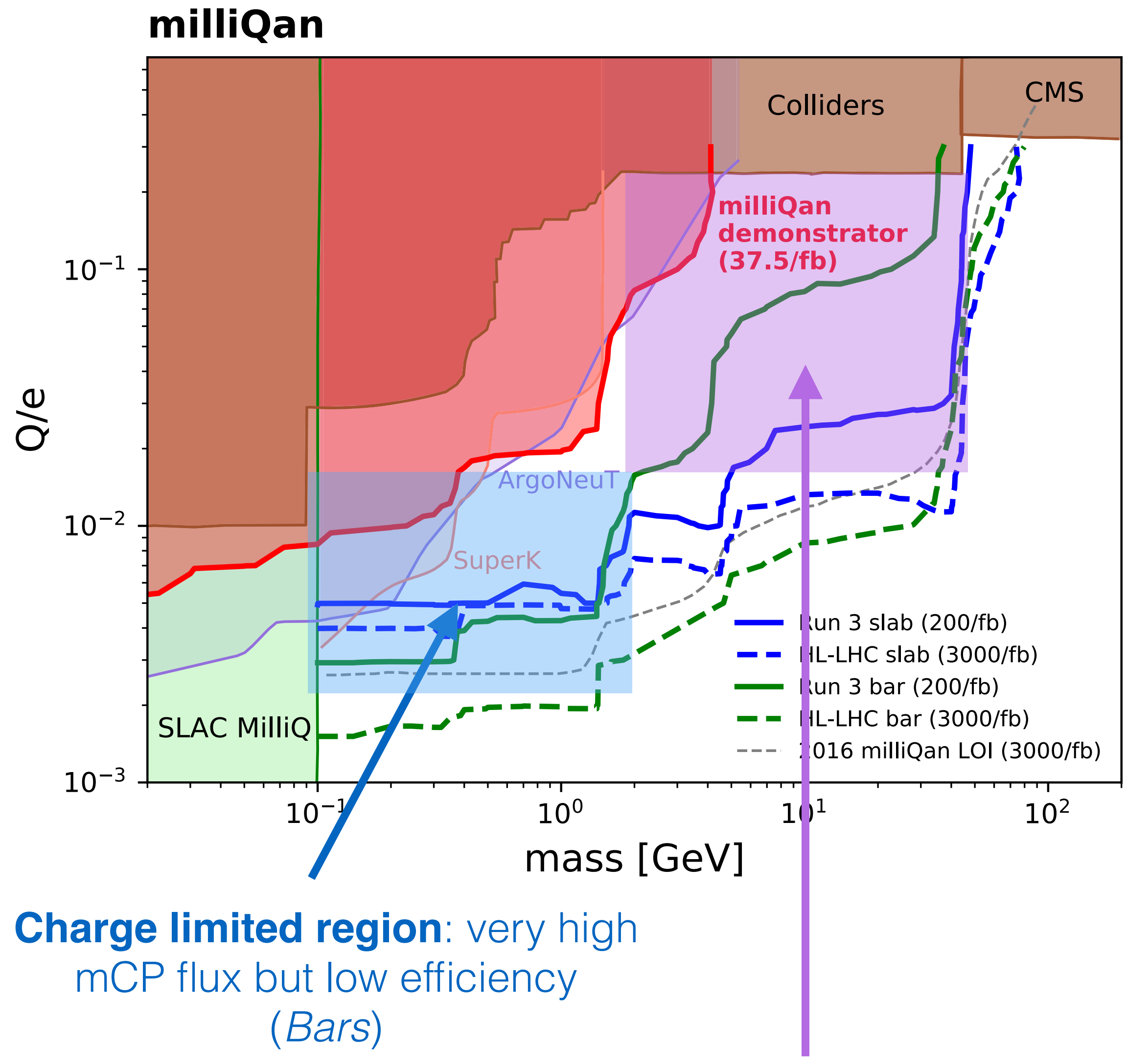




Improved Sensitivity for LHC Run 3

- Incorporated lessons learned in Run 3 detector design
    - *Added 4th layer*
    - *Added FPGA based trigger logic*
    - *Added 2nd array*
- Published expected sensitivity for new design in 2021
    - *The milliQan Run 3 detector will probe a significant chunk of unexplored parameter space*

[Phys. Rev. D **104**, 032002]

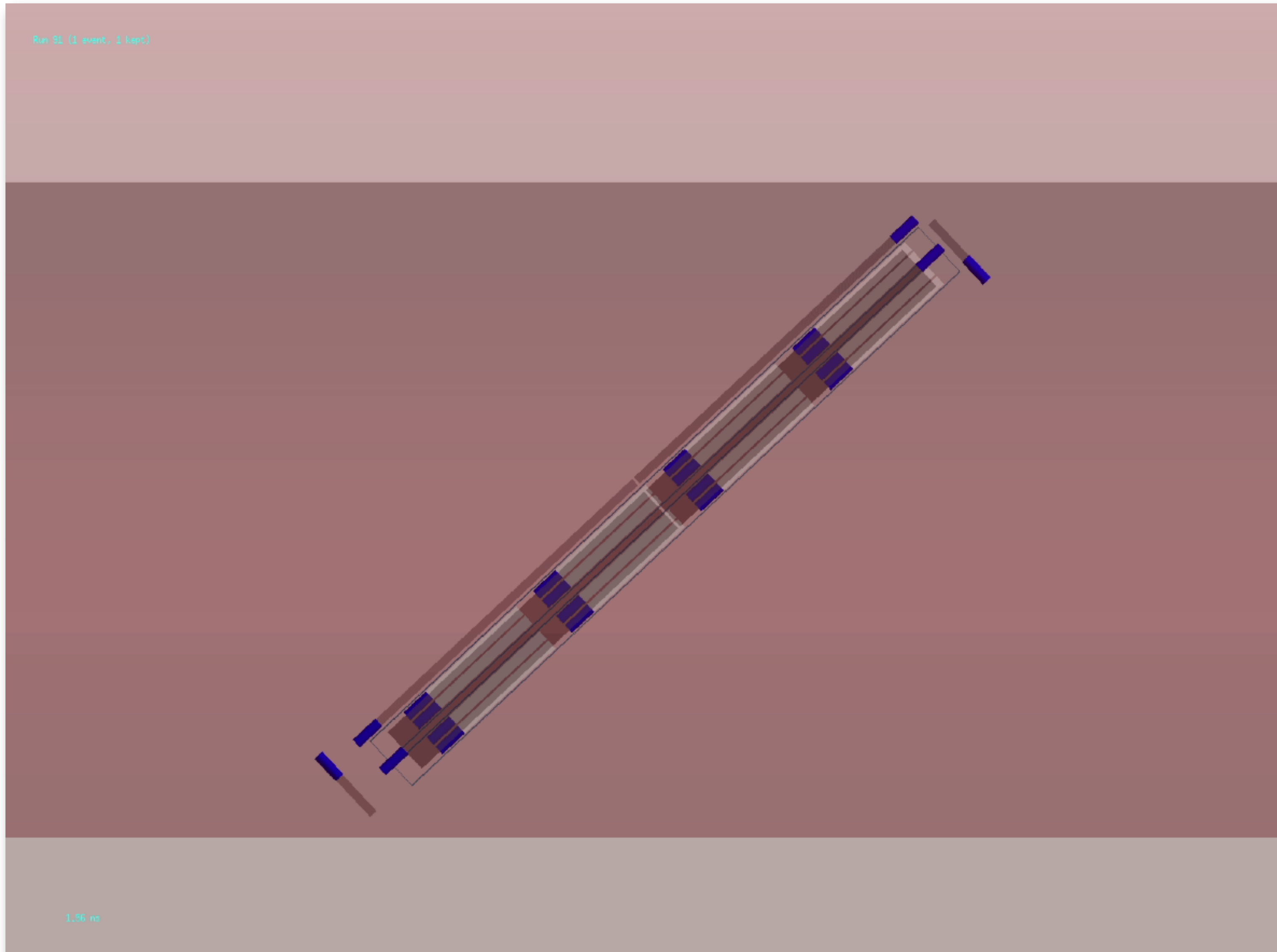


Charge limited region: very high mCP flux but low efficiency (*Bars*)

Acceptance limited region: high efficiency but mCP flux is low (*Slabs*)

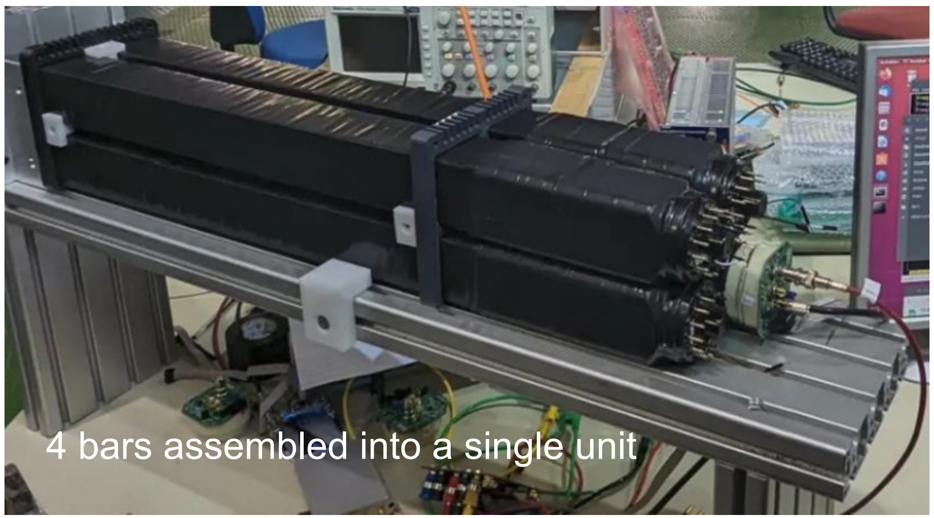
Residual Background

- With quad coincidence, random backgrounds negligible
- Dominant remaining background from cosmic ray showers
    - *Correlated hits between layers*
- Veto by thin scintillator "panels" surrounding detector



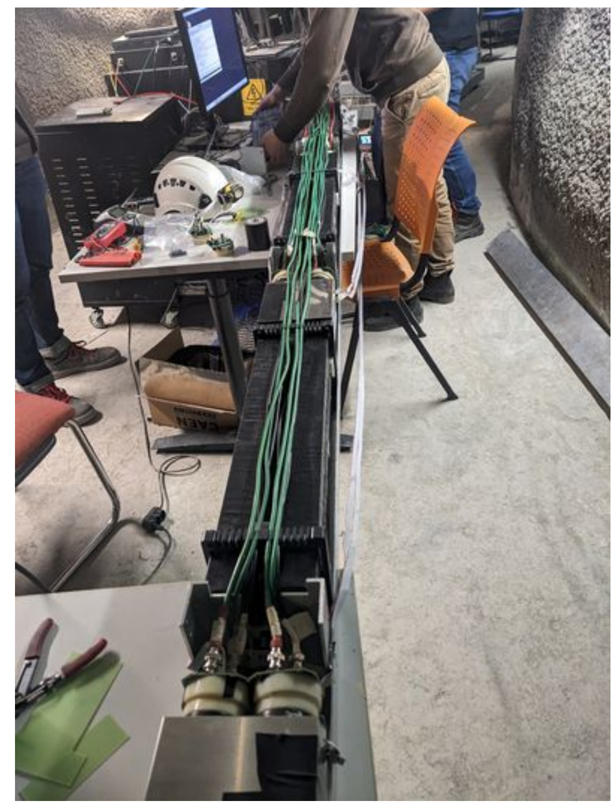
Bar Detector Construction/Installation

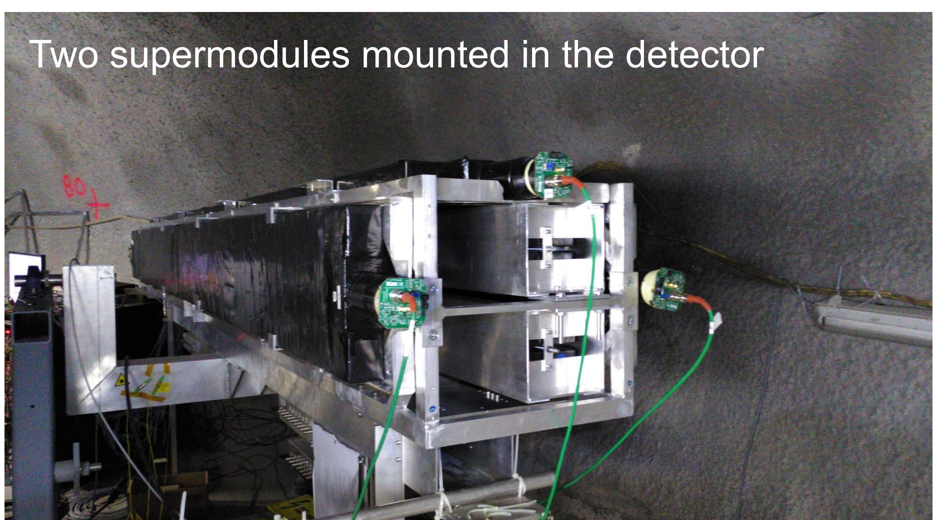
- “Modules” built at US institutes in Winter/Spring 2022
- Installed in PX56 in Summer/Fall 2022, finished Winter 2023



4 bars assembled into a single unit

Supermodule assembly using 4 units

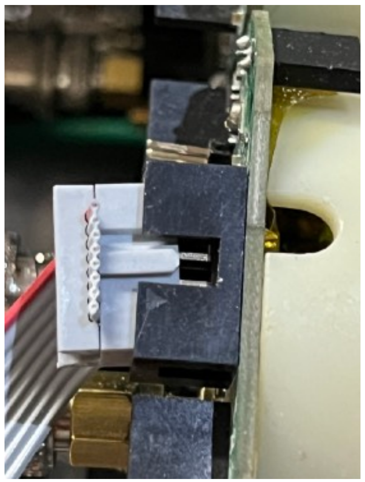




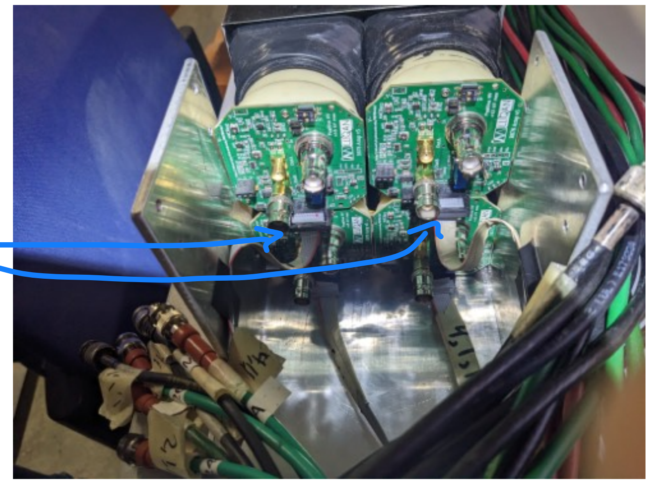
Two supermodules mounted in the detector

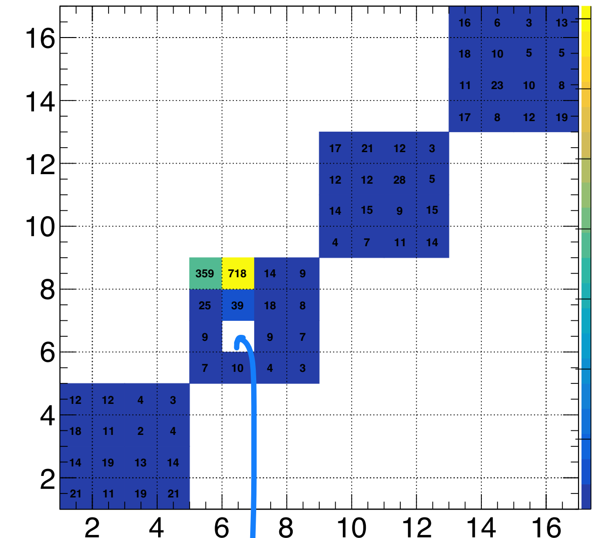
Bar Detector Commissioned

- Fixed “usual” problems that arose during installation in Spring 2023
  - *All channels now fully operational*

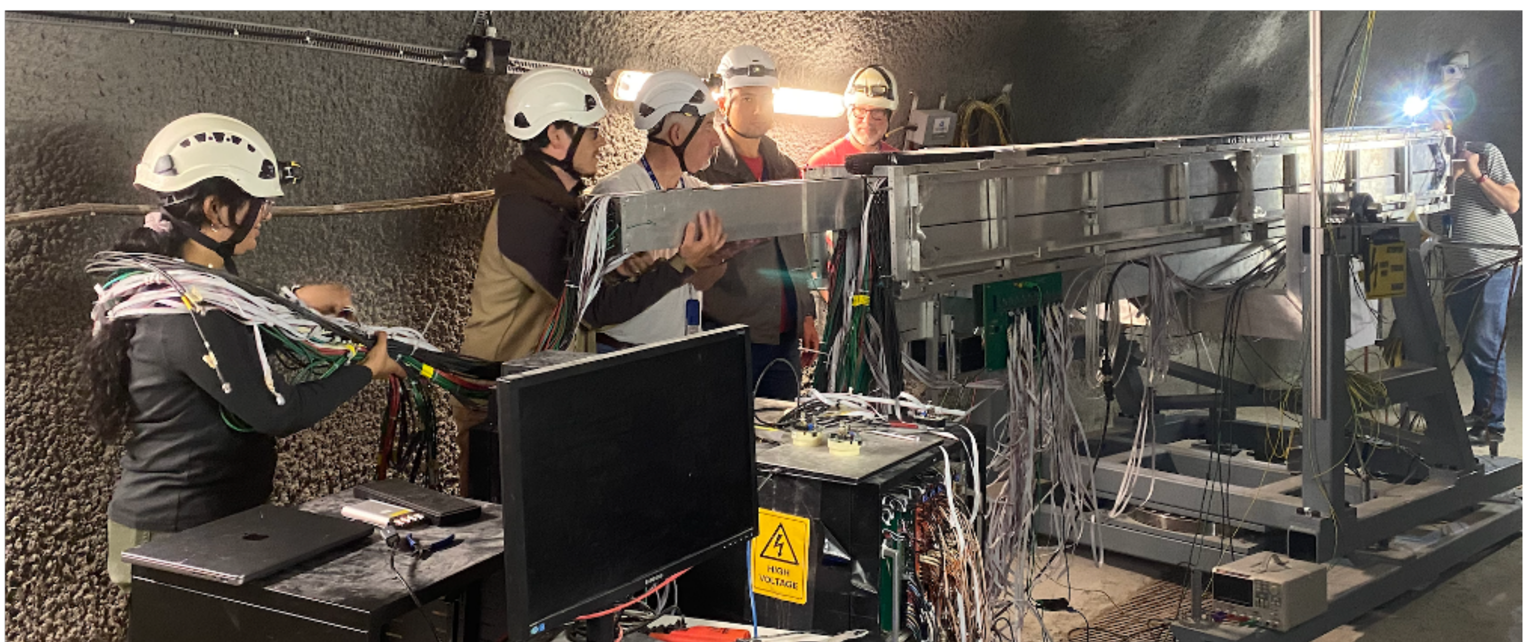


simple fix



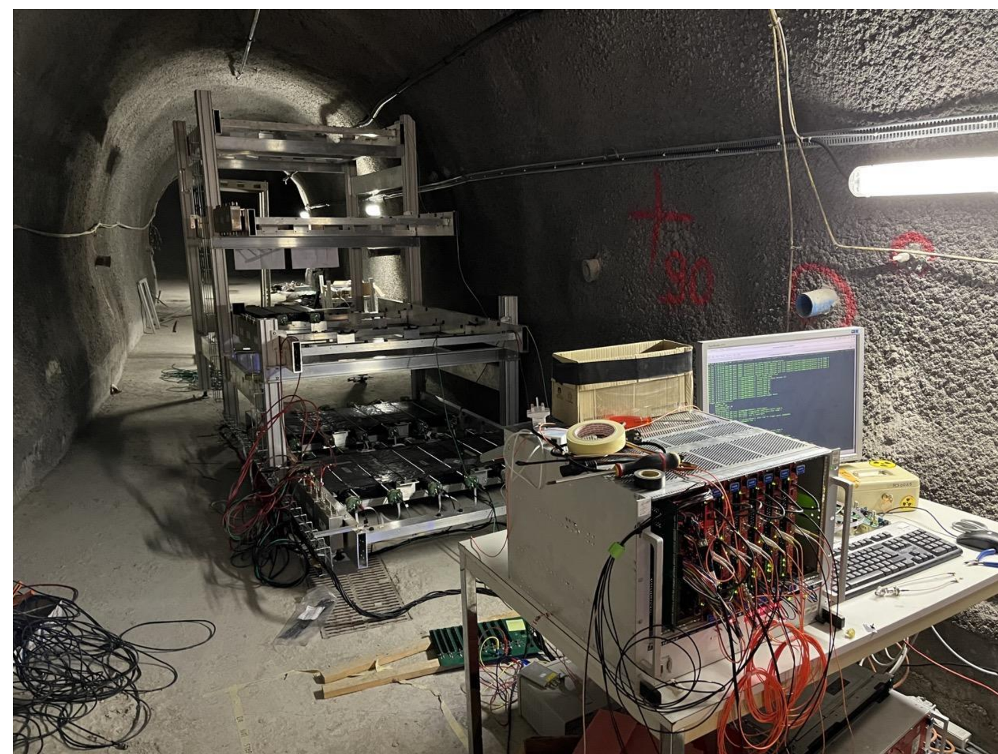


CAEN digitizer channel problem



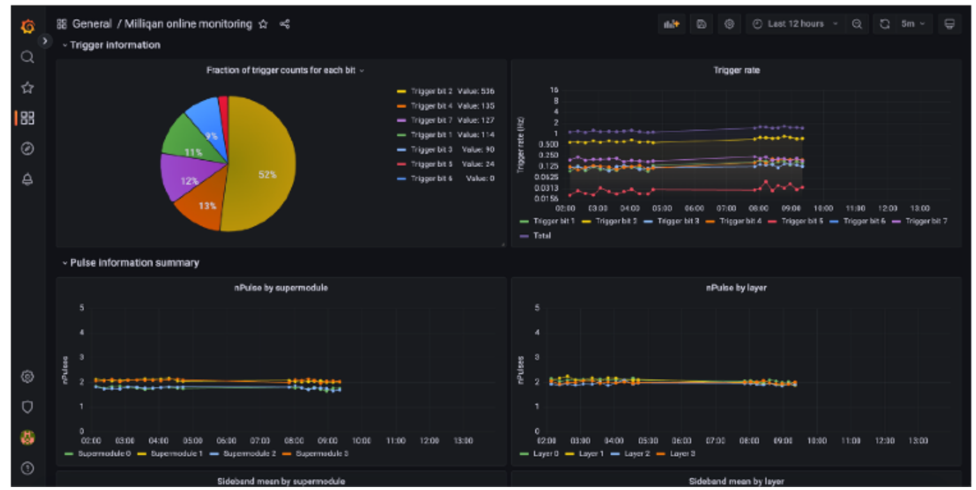
Slab Detector Construction/Installation

- Slab modules built at US institutes Summer 2022
    - *Mechanics built at CERN, installed June 2023*
- 1st layer of slab modules in place, remainder will be installed by end of Summer 2023
    - *Currently taking commissioning data with 1st layer!*



Remote DAQ & Trigger Monitoring

- Web-based interfaces/DBs to run & monitor the detector
    - *Stable continuous data taking since June 1st*



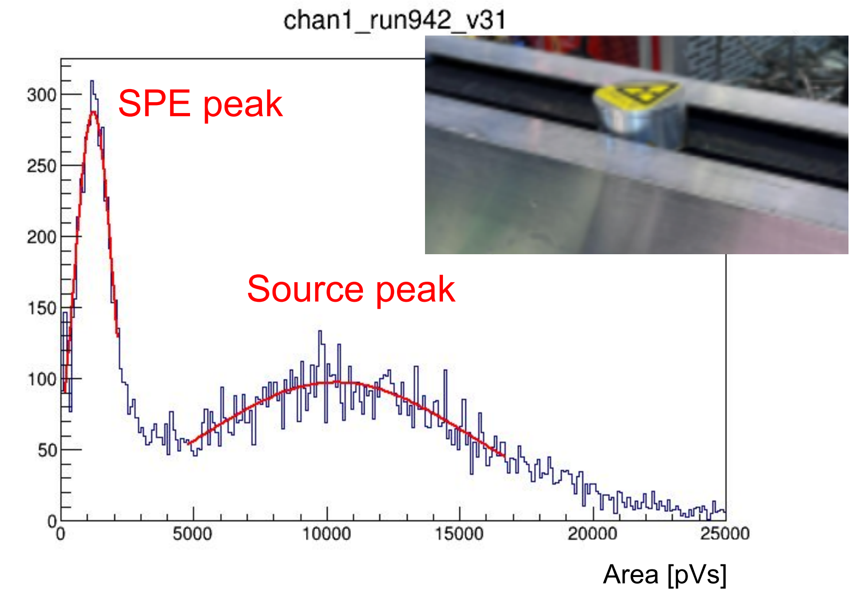
dominant trigger still 3 in a row

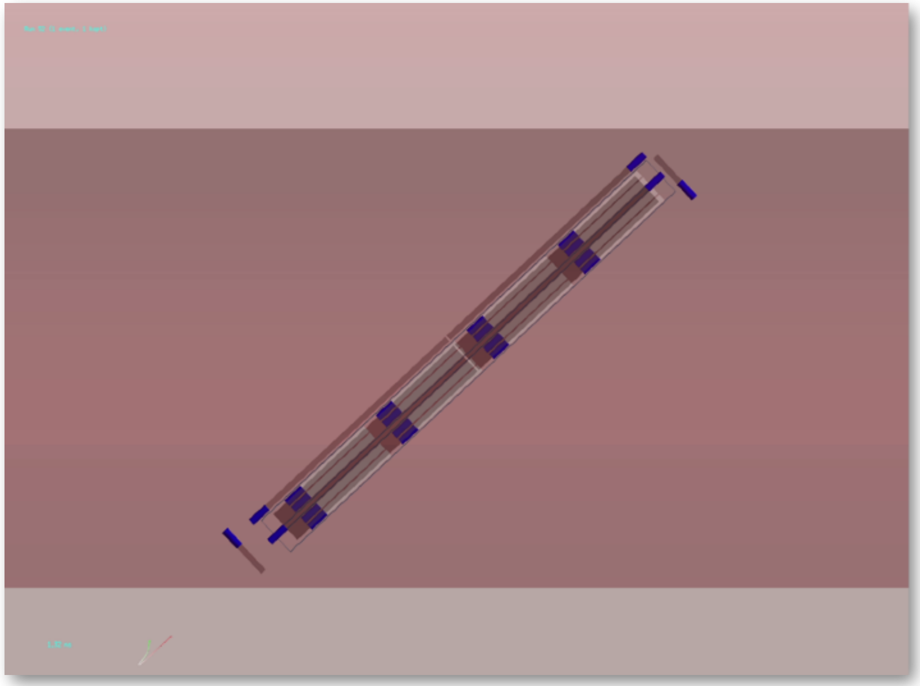
zero bias 0.5Hz

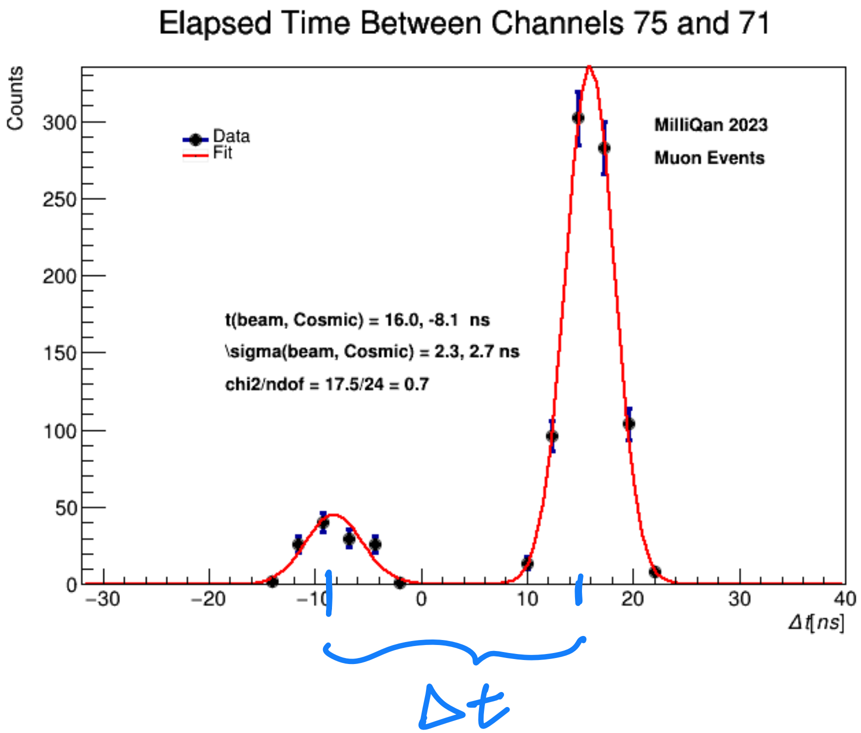
cosmics top+bot

Alignment & Calibration

- Combination of radioactive sources + integrated LEDs allow energy calibration
  - *e.g. nPE/keV from ^{109}Cd (for bars)*
- Thoroughgoing muons from CMS IP used for timing calibration + alignment
  - *Expected cross-section is ~1/pb^{-1} , measurement in progress …*

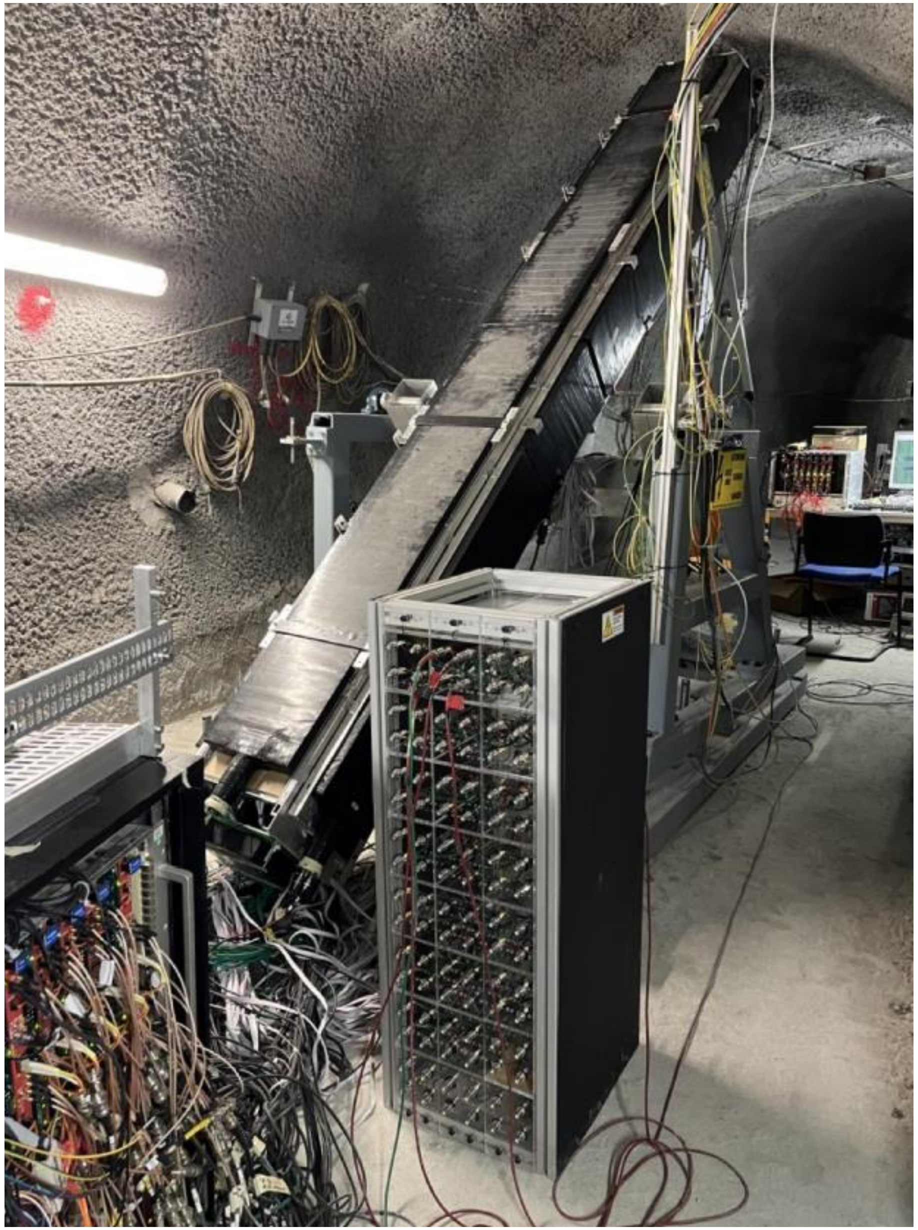






Summary & Outlook

- **milliQan** is two dedicated detectors sensitive to **millicharged particles** (mCPs) produced by LHC at CMS IP
    - *Complementary approach to probe dark sector*
    - *Sensitive to Q/e < 0.3 particles over wide mass range 100 MeV — 100 GeV*
- Bar detector is fully assembled, taking physics data!
- Slab detector being assembled, will be fully commissioned by end of summer 2023
- Currently analyzing collision data from LHC Run 3 produced by both detectors
    - *milliQan will collect ~30 fb^{-1} in 2023*
    - *First physics results by ~Winter 2024!*



Additional Material

THE MILLIQAN EXPERIMENT

THE OHIO STATE UNIVERSITY

UNIVERSITY OF CALIFORNIA SANTA BARBARA

THE UNIVERSITY OF CALIFORNIA DAVIS

NYU

CERN

University of BRISTOL

THE UNIVERSITY OF CHICAGO 1890

الجامعة اللبنانية
UNIVERSITE LIBANAISE

THE UNIVERSITY OF CALIFORNIA IRVINE

VUB VRIJE UNIVERSITEIT BRUSSEL

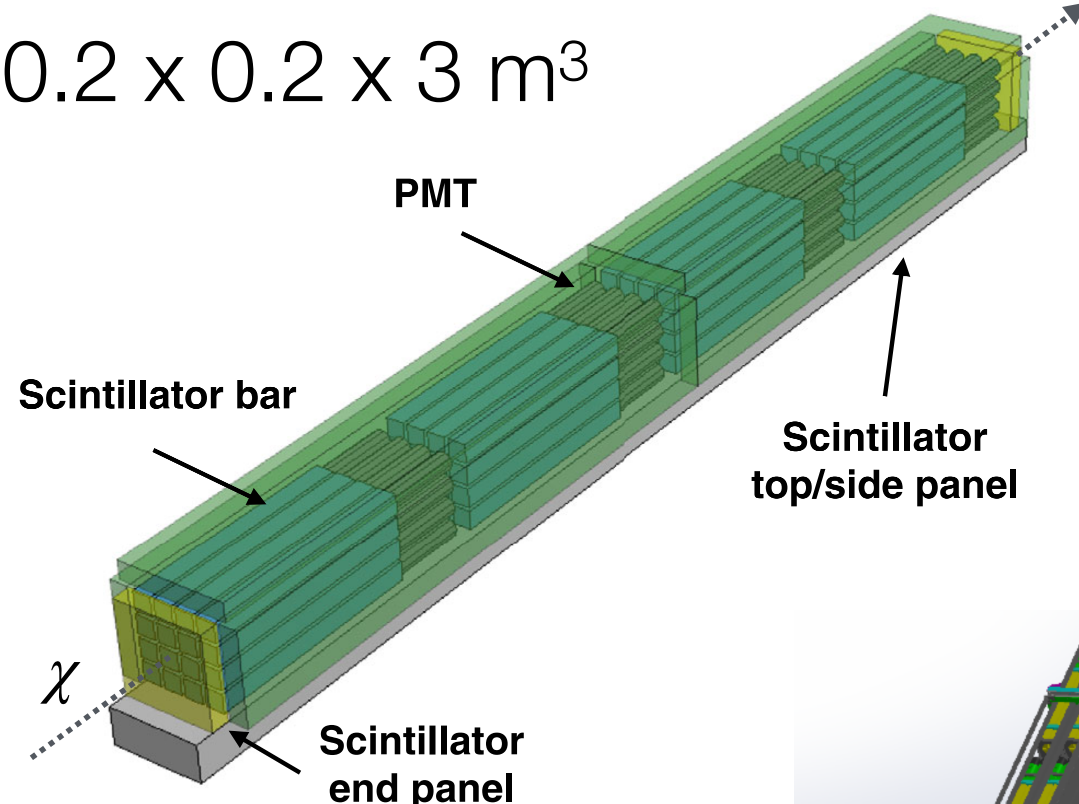
UNIVERSITY OF Nebraska Lincoln

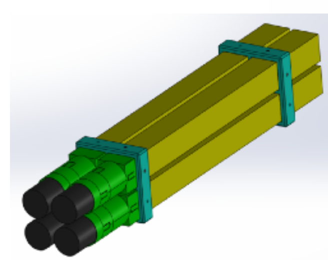
milliQan Collaboration meeting 2022

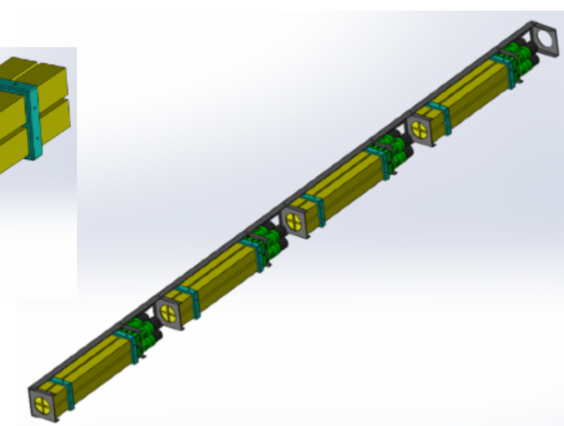
Run 3 Bar Detector Design

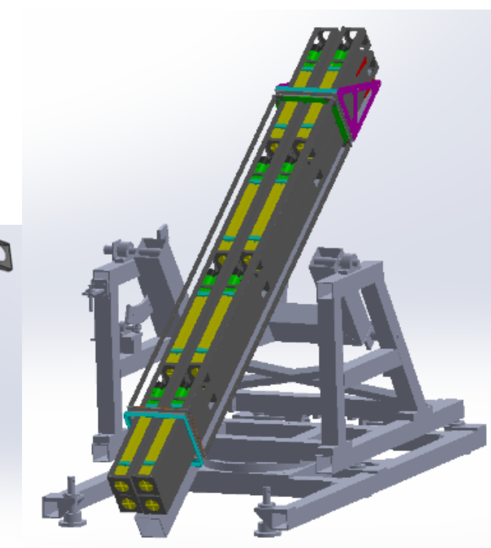
- Bar detector for Run 3 is a straightforward upgrade of the demonstrator
  - *Optimized for **charge limited region***
  - *Expanded size*
  - *4 layers of 4x4 scintillator bars*
  - *Each layer contains 5 x 5 x 60 cm³ bars*
  - *Thicker veto panels*
  - *Re-uses retractable support installed with demonstrator*

~0.2 x 0.2 x 3 m³



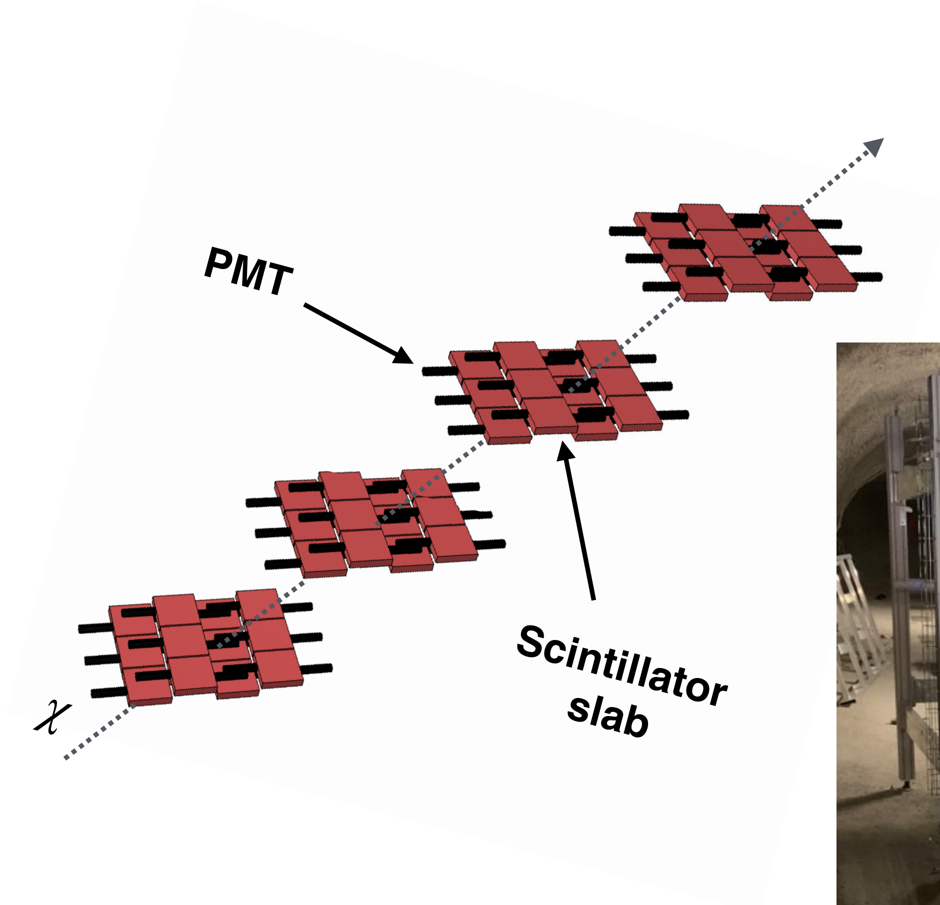


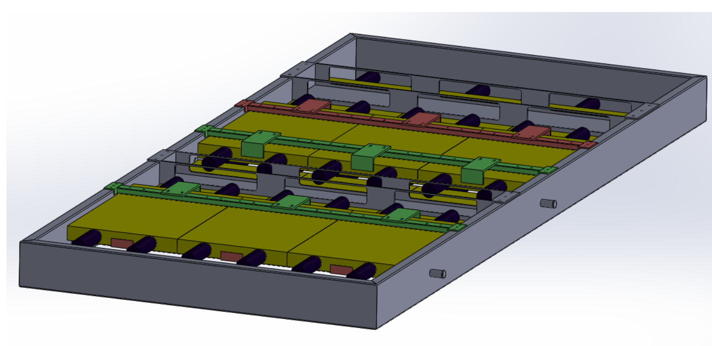




Run 3 Slab Detector Design

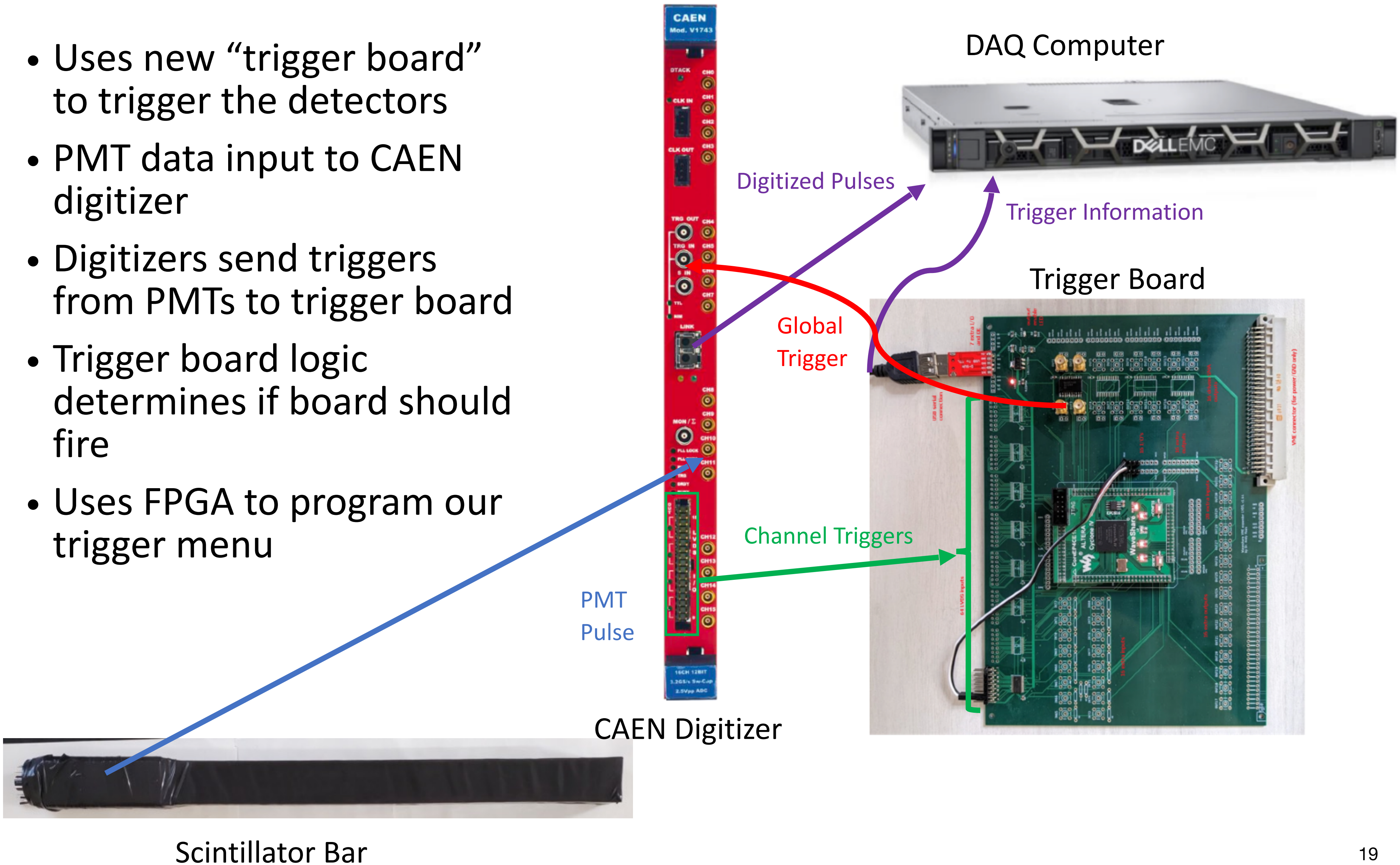
- Optimized for **acceptance limited region**
    - *Covers large area for low cost*
    - *4 layers of 12 40 x 60 x 5 cm "slabs"*
        - **Surface area equivalent to ~1100 5 x 5 cm bars!**
    - *Efficient down to Q/e~0.01e*
    - *2 PMTs (summed together) on both ends of slab for optimal light collection*
        - **4 PMTs total per slab**





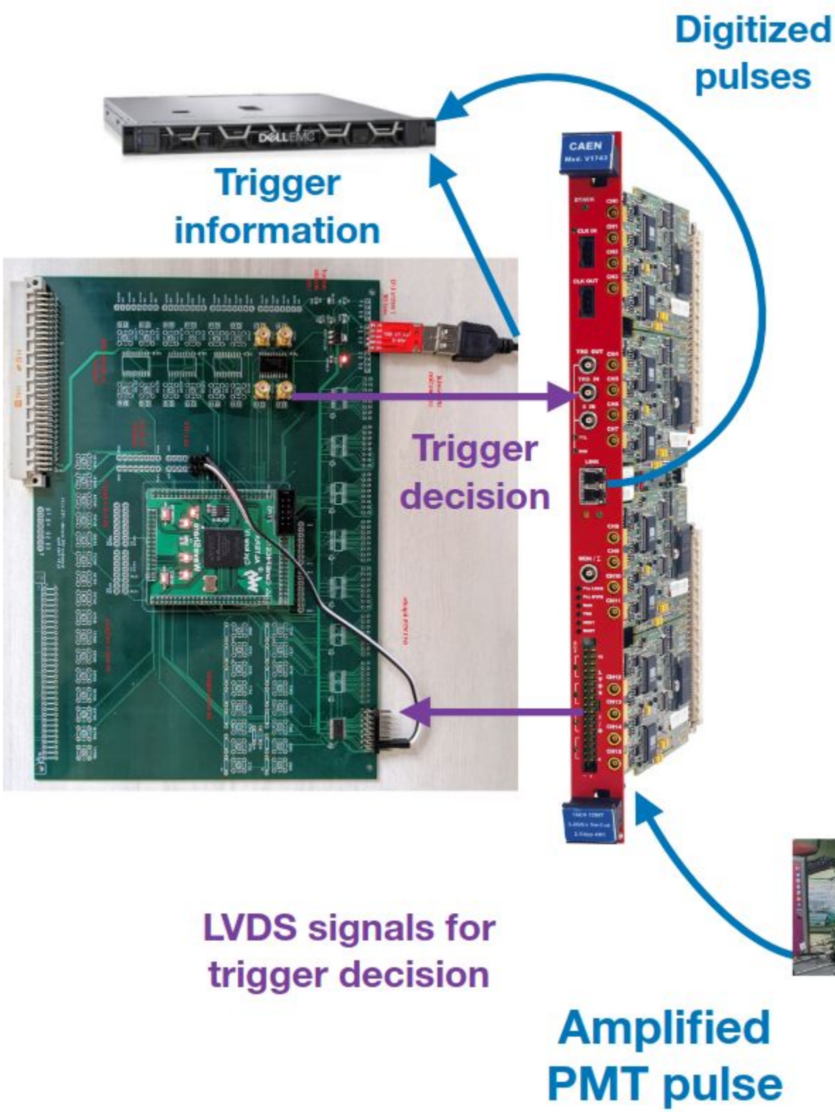
Trigger and DAQ

- Uses new “trigger board” to trigger the detectors
- PMT data input to CAEN digitizer
- Digitizers send triggers from PMTs to trigger board
- Trigger board logic determines if board should fire
- Uses FPGA to program our trigger menu



Bar Trigger and DAQ (Slab ~same)

- Amplified output from each bar is recorded using a 16 channel CAEN digitizer with 0.4 GHz sampling frequency and 2.5 μs readout window
- Trigger decisions are made using a customized trigger board with Altera Cyclone IV FPGA



Bonus Physics - Heavy Neutrino EDM

- milliQan also sensitive to BSM signals besides mCPs that would produce a small energy loss in matter
  - *e.g. electric dipole moment from a heavy neutrino*

$$\Delta E = \frac{|\Delta \vec{p}|^2}{2m} = \frac{e^4 D^2}{2m(4\pi\epsilon_0)^2(vb^2)^2}.$$

Physics Letters B 777 (2018) 246–249

Contents lists available at ScienceDirect

Physics Letters B

www.elsevier.com/locate/physletb

Detecting a heavy neutrino electric dipole moment at the LHC

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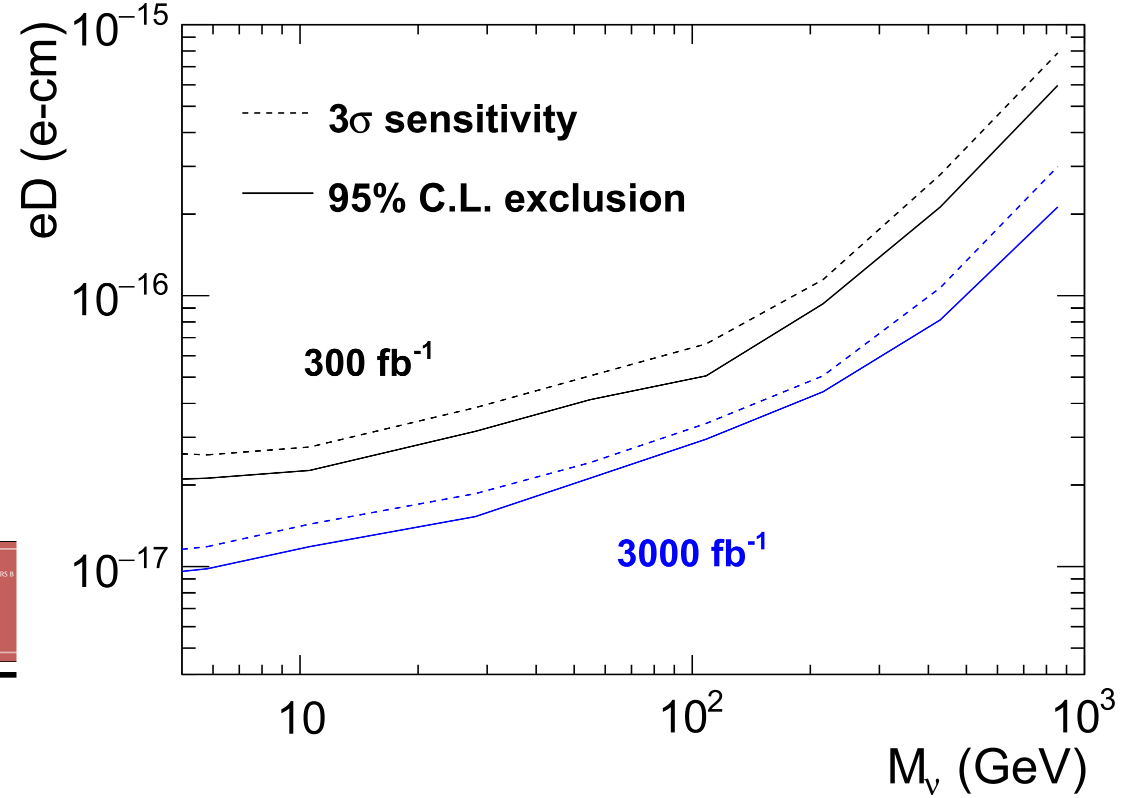
ARTICLE INFO

Article history:
Received 23 October 2017
Received in revised form 7 December 2017
Accepted 8 December 2017
Available online 12 December 2017
Editor: M. Cvetič

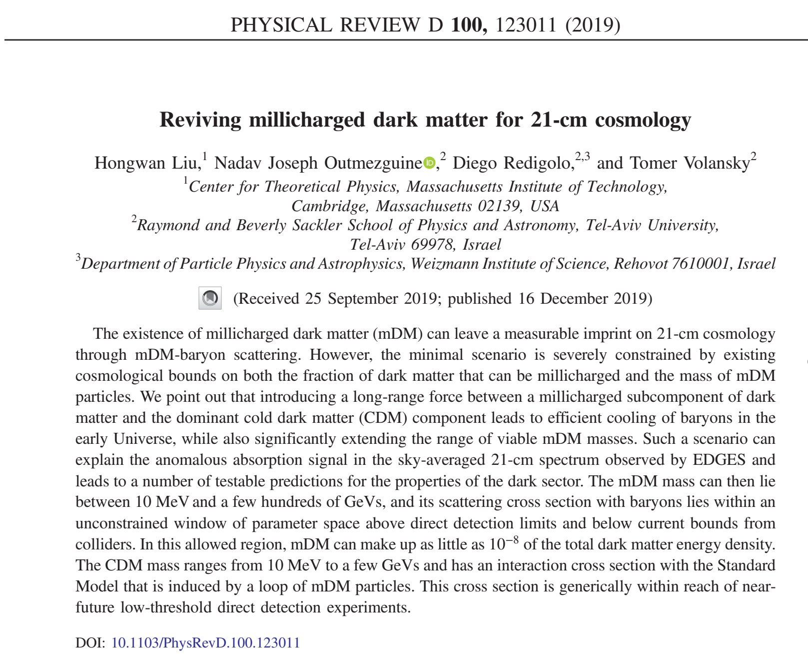
ABSTRACT

The milliQan Collaboration has proposed to search for millicharged particles by looking for very weakly ionizing tracks in a detector installed in a cavern near the CMS experiment at the LHC. We note that another form of exotica can also yield weakly ionizing tracks. If a heavy neutrino has an electric dipole moment (EDM), then the milliQan experiment may be sensitive to it as well. In particular, writing the general dimension-5 operator for an EDM with a scale of a TeV and a one-loop factor, one finds a potential EDM as high as a few times 10^{-17} e-cm, and models exist where it is an order of magnitude higher. Redoing the Bethe calculation of ionization energy loss for an EDM, it is found that the milliQan detector is sensitive to EDMs as small as 10^{-17} e-cm. Using the production cross-section and analyzing the acceptance of the milliQan detector, we find the expected 95% exclusion and 3σ sensitivity over the range of neutrino masses from 5–1000 GeV for integrated luminosities of 300 and 3000 fb^{-1} at the LHC.



EDGES Anomaly

- Liu et al. in PRD **100** 123011 (2019)
    - *“In the near future, the installation of milliQan at CERN [99] can cover a large portion of the EDGES explanation up to a fraction $f_m \sim 10^{-6}$”*



PHYSICAL REVIEW D **100,** 123011 (2019)

Reviving millicharged dark matter for 21-cm cosmology

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(Received 25 September 2019; published 16 December 2019)

The existence of millicharged dark matter (mDM) can leave a measurable imprint on 21-cm cosmology through mDM-baryon scattering. However, the minimal scenario is severely constrained by existing cosmological bounds on both the fraction of dark matter that can be millicharged and the mass of mDM particles. We point out that introducing a long-range force between a millicharged subcomponent of dark matter and the dominant cold dark matter (CDM) component leads to efficient cooling of baryons in the early Universe, while also significantly extending the range of viable mDM masses. Such a scenario can explain the anomalous absorption signal in the sky-averaged 21-cm spectrum observed by EDGES and leads to a number of testable predictions for the properties of the dark sector. The mDM mass can then lie between 10 MeV and a few hundreds of GeVs, and its scattering cross section with baryons lies within an unconstrained window of parameter space above direct detection limits and below current bounds from colliders. In this allowed region, mDM can make up as little as 10^{-8} of the total dark matter energy density. The CDM mass ranges from 10 MeV to a few GeVs and has an interaction cross section with the Standard Model that is induced by a loop of mDM particles. This cross section is generically within reach of near-future low-threshold direct detection experiments.

DOI: 10.1103/PhysRevD.100.123011