MilliQan Run 3 Detector

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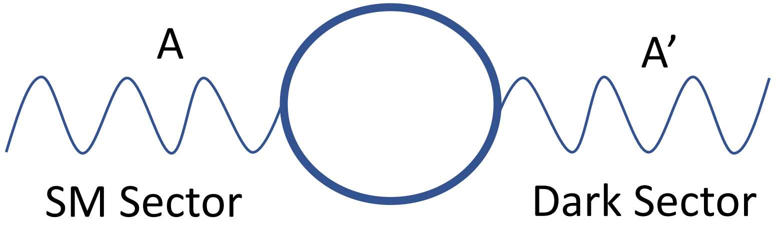
What is a Millicharged Particle?

- Millicharged particles (mCP) are theorized particles that have fractional electron charge
- Particles would come from a “dark QED” field A'
- This field mixes with hypercharge creating the millicharged particle ψ with mass M_{mCP}
- Redefining $A'_\mu \rightarrow A'_\mu + \kappa B_\mu$results in a coupling between ψ and hypercharge $\kappa e'$
- And a coupling to the photon gives a charge $\epsilon = \kappa e' cos\theta_w / e$

$$\mathcal{L} = \mathcal{L}_{SM} - \underbrace{\frac{1}{4}A'_{\nu\mu}A'^{\mu\nu}}_{\text{Dark Photon Term}} + \underbrace{i\bar{\psi}(\not{\partial} + ie'\not{A}' + iM_{mCP})\psi}_{\text{Dark Fermion}} - \underbrace{\frac{\kappa}{2}A'_{\mu\nu}B^{\mu\nu}}_{\text{Kinetic Mixing Term}}$$

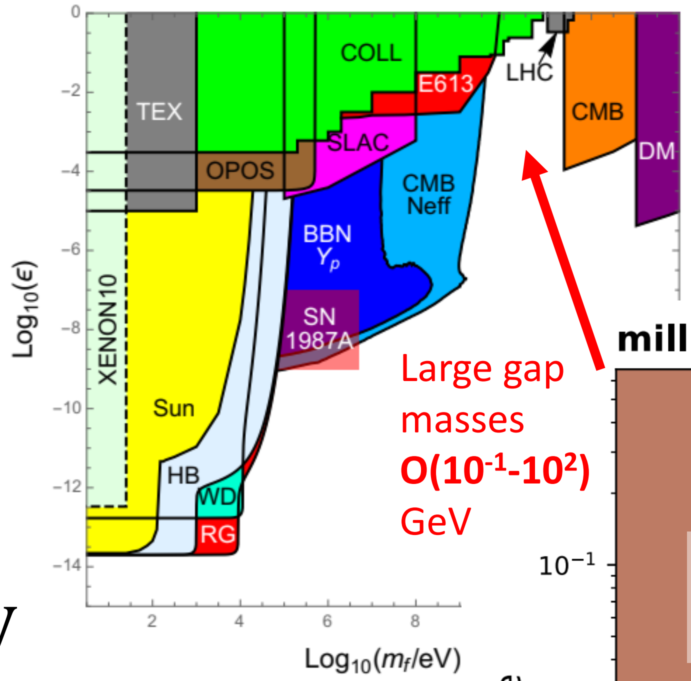


$$\mathcal{L} = \mathcal{L}_{SM} - \frac{1}{4}A'_{\nu\mu}A'^{\mu\nu} + i\bar{\psi}(\not{\partial} + ie'\not{A}' + -i\kappa e'\not{B} + iM_{mCP})\psi$$

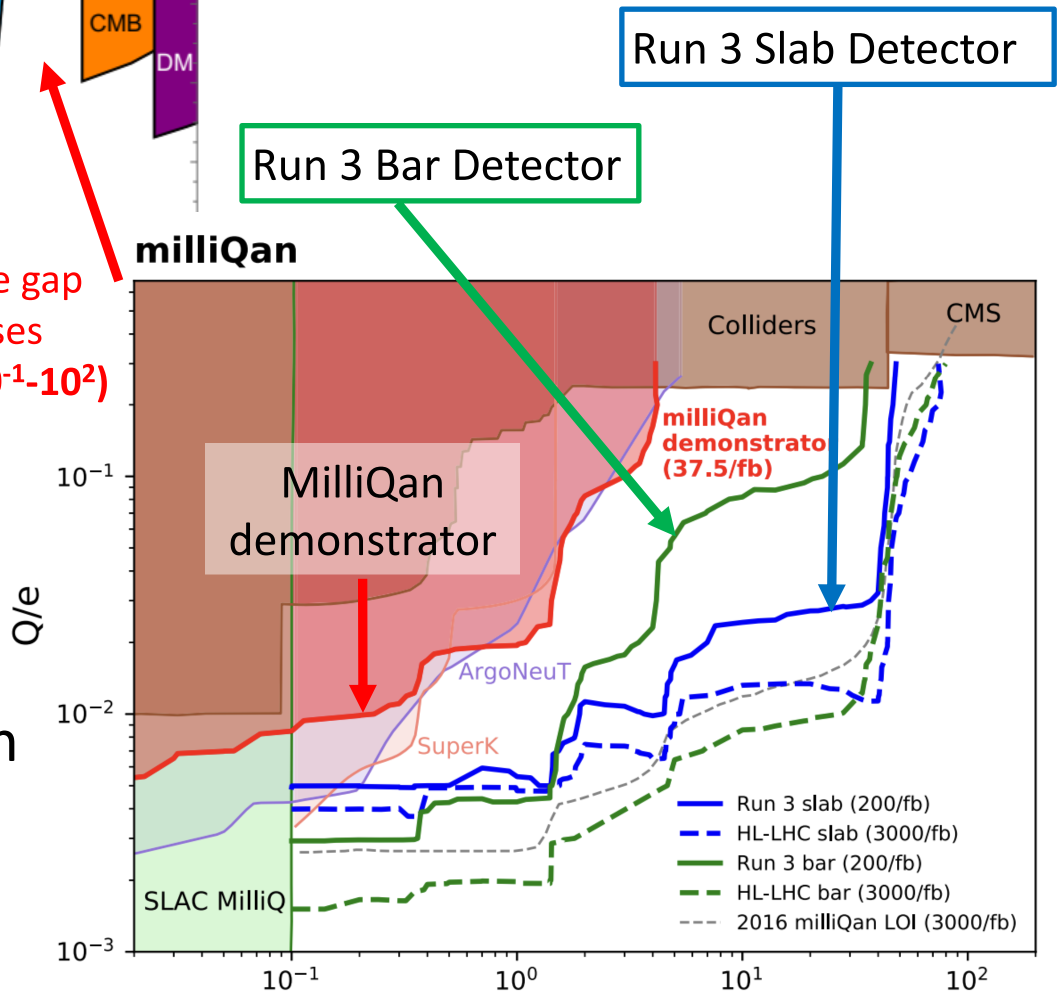
Improving Sensitivity

- Limits set on mCPs in effective charge (ϵ) and mass
  - Cosmological limits (left)
  - Collider experiments (CMS, SLAC MilliQ, etc) (right)
- milliQan detector aims to **probe undetected phase** space
  - $10^{-1} GeV < M_{mCP} < 10^{2}\mathrm{GeV}$
  - $10^{-3} < \frac{Q}{e} < 10$
- Bar & slab detector expected to set new sensitivity in run 3

arXiv:1511.01122v2



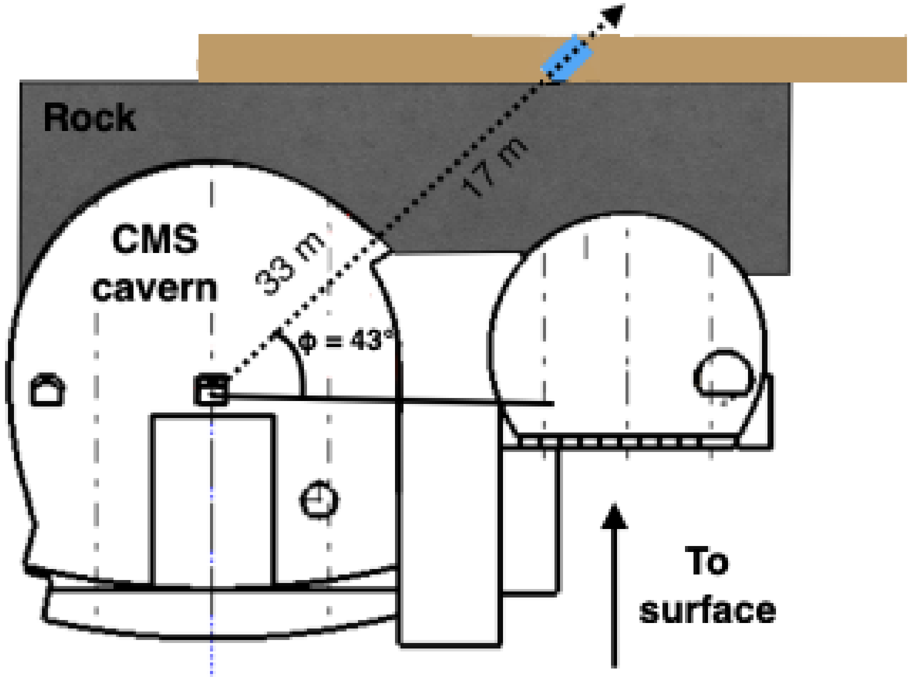
Large gap masses
O(10^-1^-10^2^)
GeV

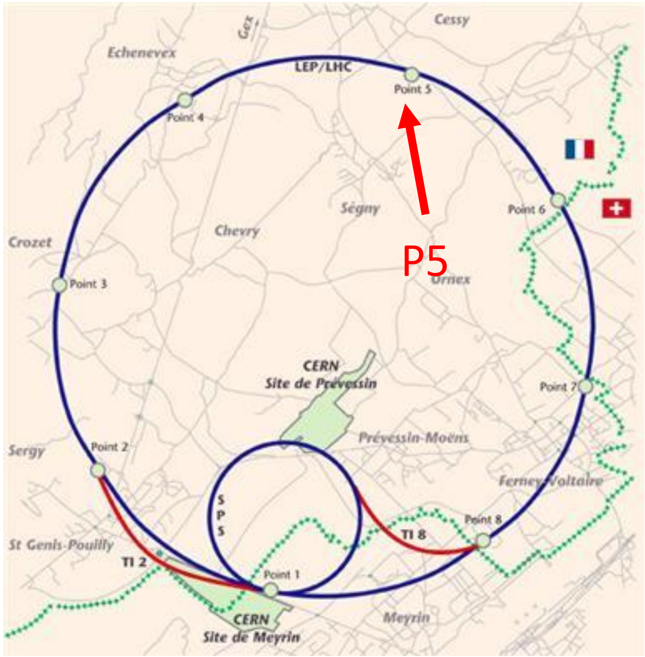


Phys. Rev. D **104**, 032002

milliQan Detector Location

- Detector in PX56 drainage gallery at P5 (above CMS)
- 33m from CMS IP at an angle $\eta \approx 0.1, \phi \approx 43$
- 17m of rock act as shielding against background

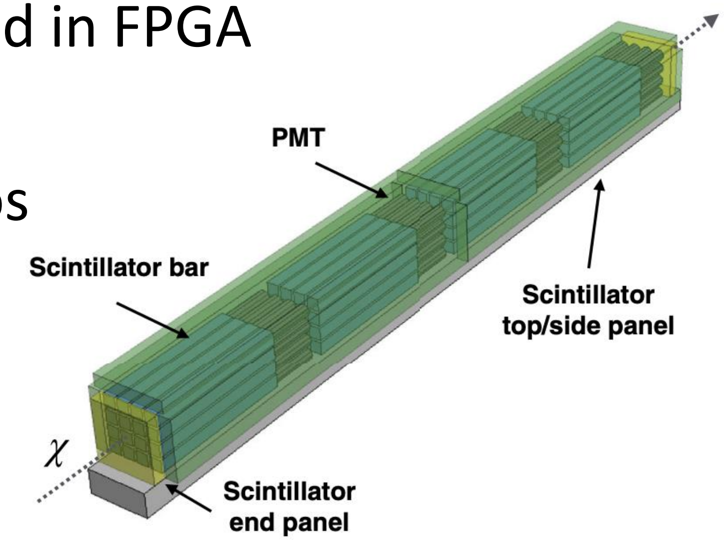


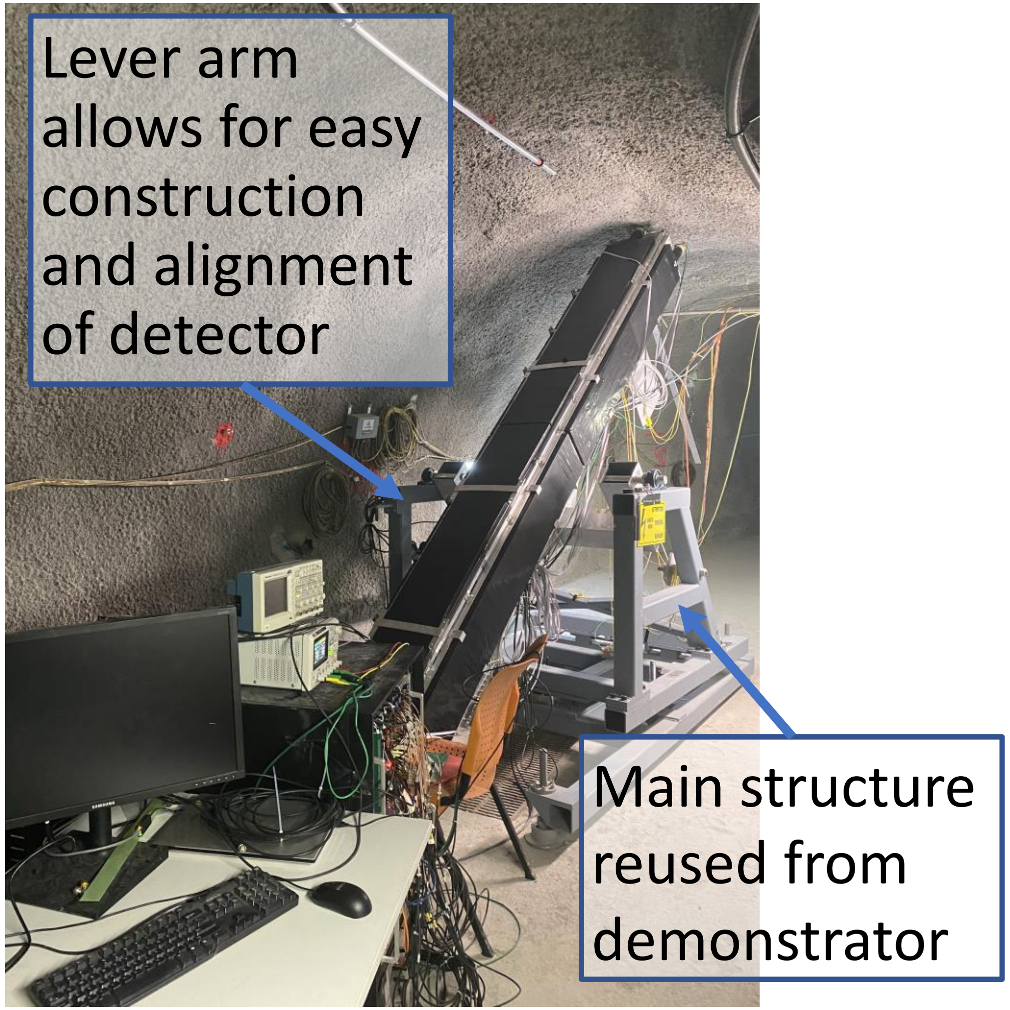


drainage gallery

milliQan Bar Detector

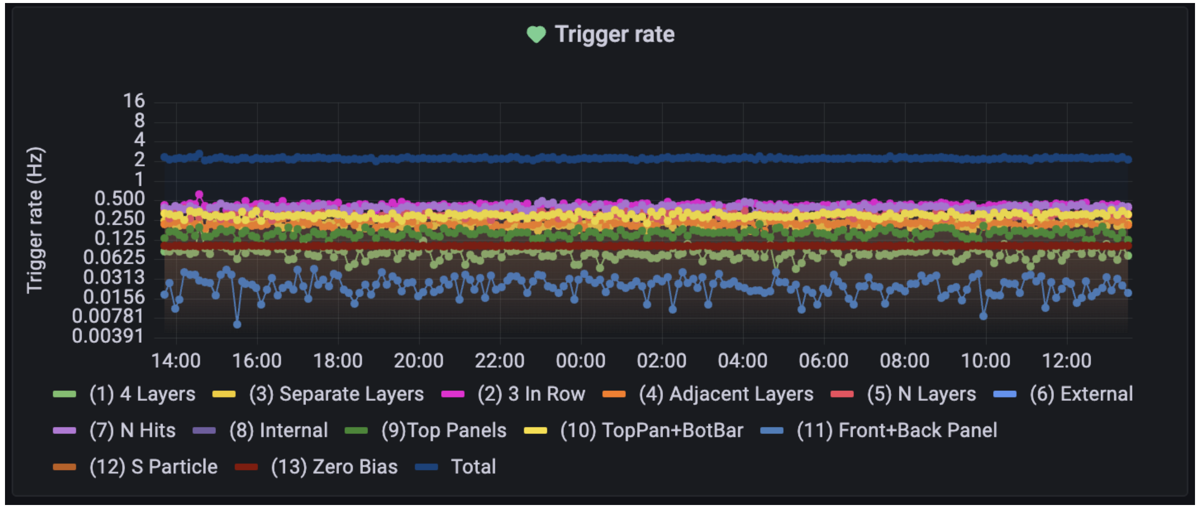
- 4 layers each composed of 16 (5x5x60cm) bars
- Scintillator panels on front and back, top and sides for background veto
- Many improvements from demonstrator:
  - Special PMT amplifiers to efficiently reconstruct single photoelectrons
  - LED flasher system for calibration of response
  - Triggers implemented in FPGA
  - Thicker panels to improve cosmic vetos
  - Readout window 4x bigger -> better analyze after pulses

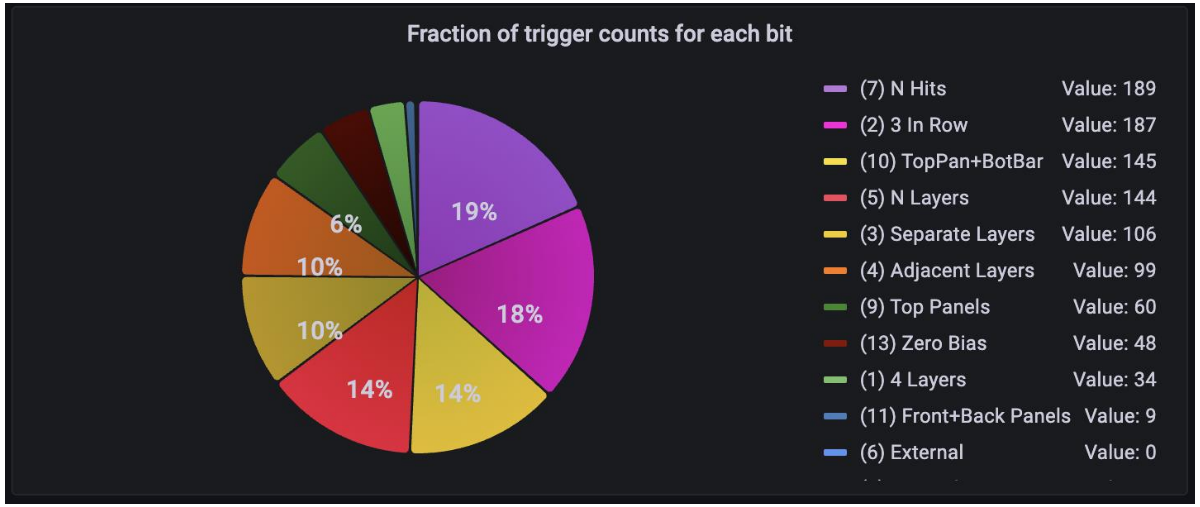




Bar Detector Run 3

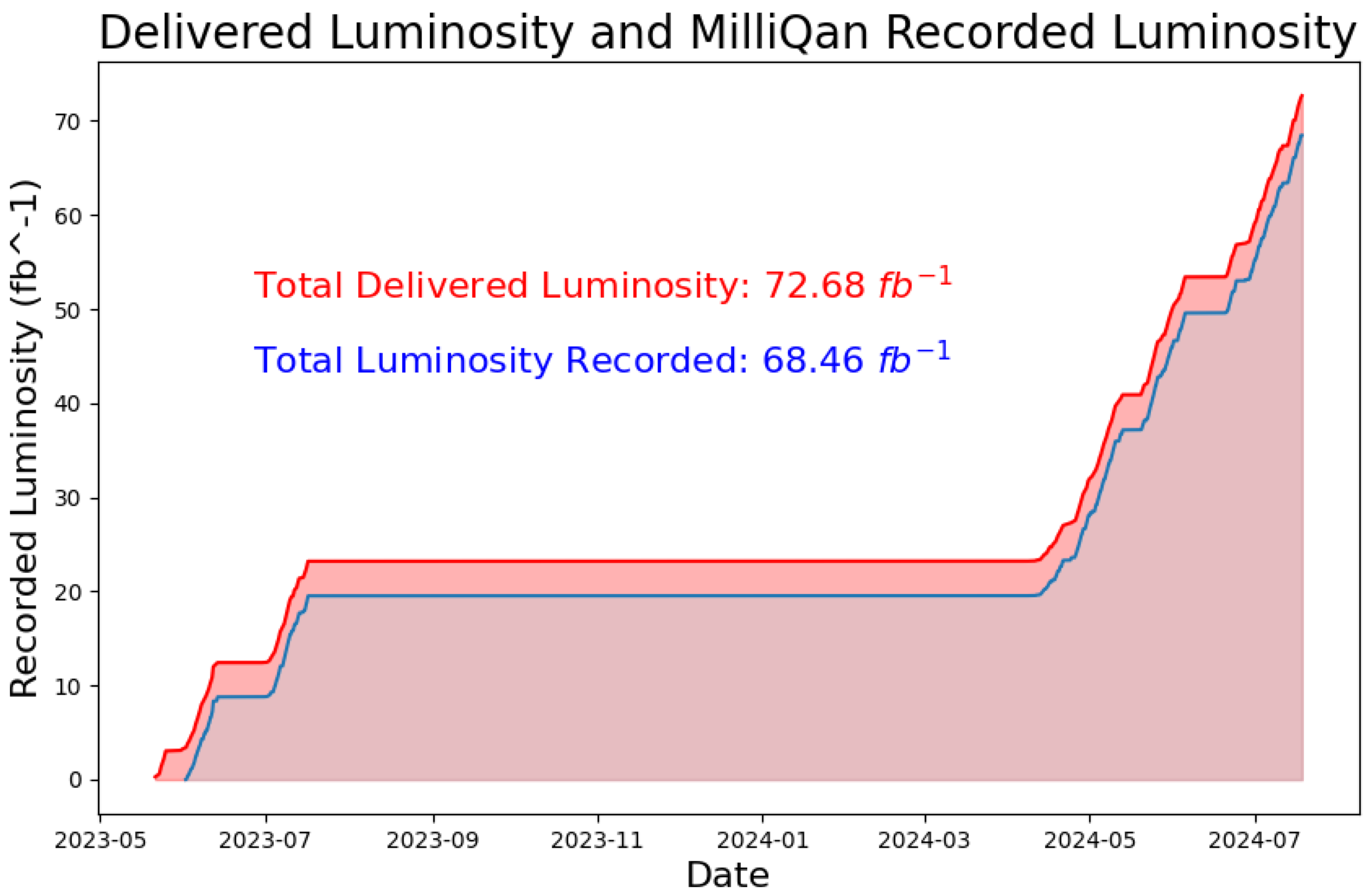
- Running and collecting data since June 2023!
- Online monitoring system to track detector status
- Signal triggers:
  - 3 hits in a line
  - 4 layers hit
- Background triggers:
  - 2 layers hit (ex. dark rate)
  - Top panels hit (ex. cosmic showers)
- Stable trigger rate ~2Hz





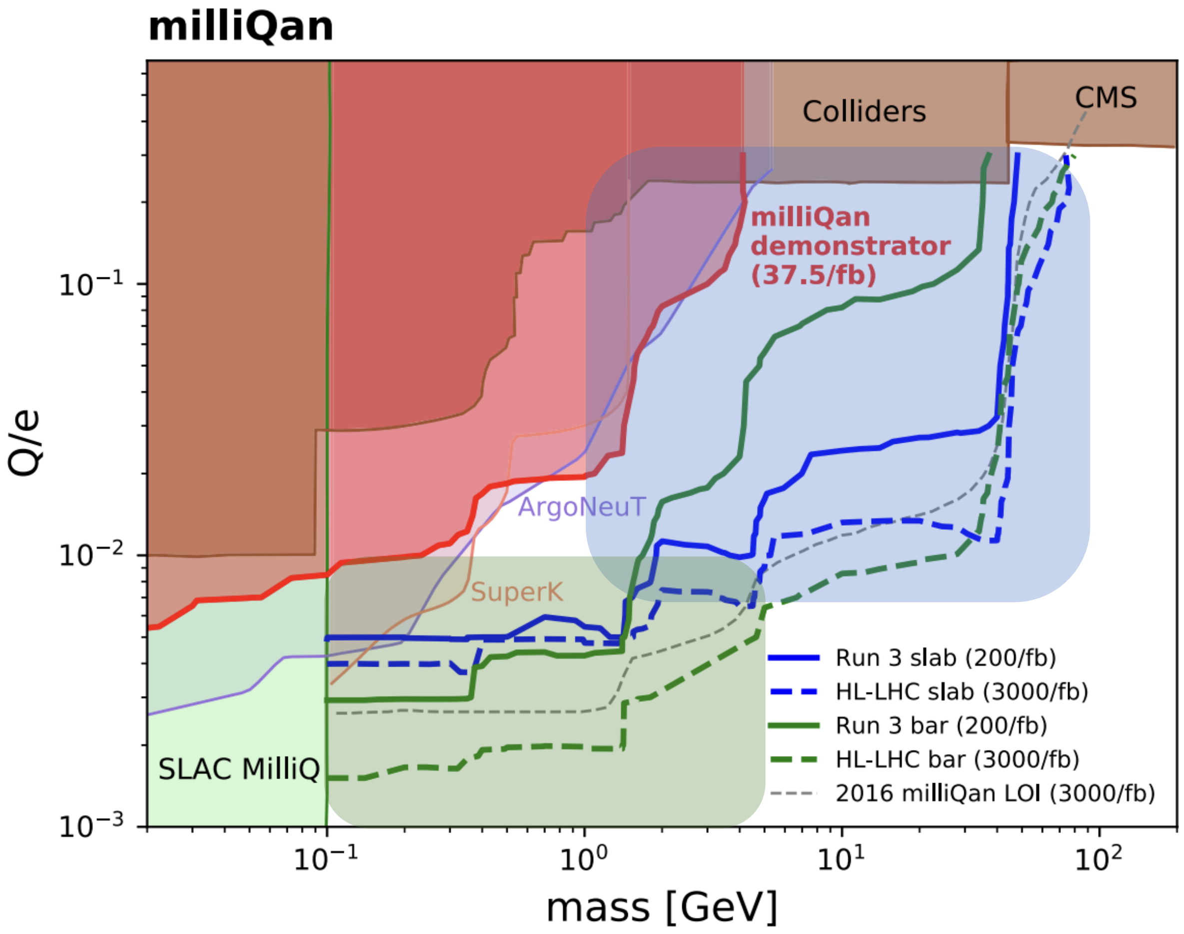
Run 3 Bar Detector Luminosity

- Collected ~72 fb^{-1} of data so far
- Detector is running 24/7
- Compared to CMS total delivered stable luminosity (red)
- Expect to collect over $100fb^{-1}$ by end of pp runs 2024



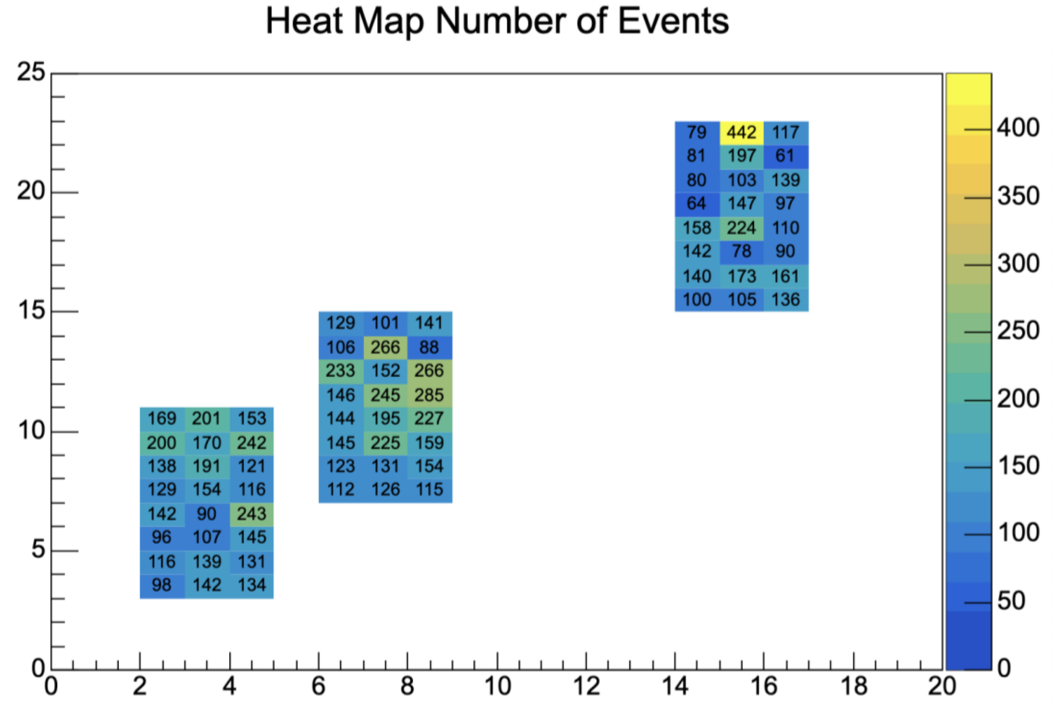
MilliQan Slab Detector

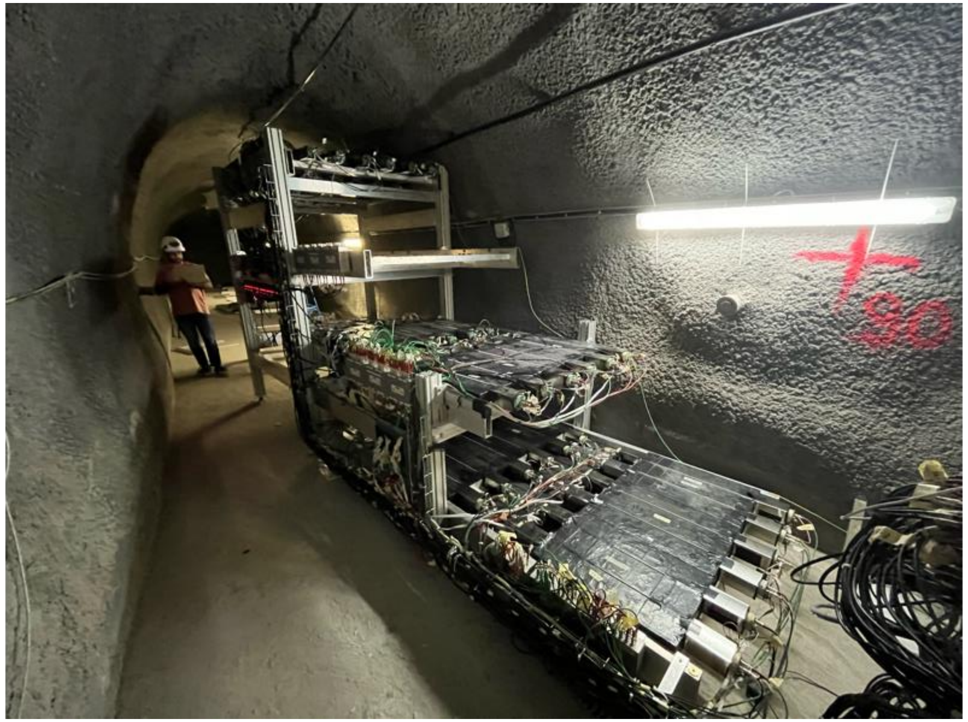
- Increasing area provides increased acceptance
- Designed slab detector covering larger area!
- Improves limits at larger mass (1-100GeV)
- 4 layers of 12 scintillator slabs (40cm x 60cm x 5cm)
- ~72x geometric acceptance of bar detector



MilliQan Slab Detector

- Slab detector construction ongoing (3.5/4 layers installed)
- Expect full detector finished within next week!
- Perform calibrations over next month and take data for 2024/25



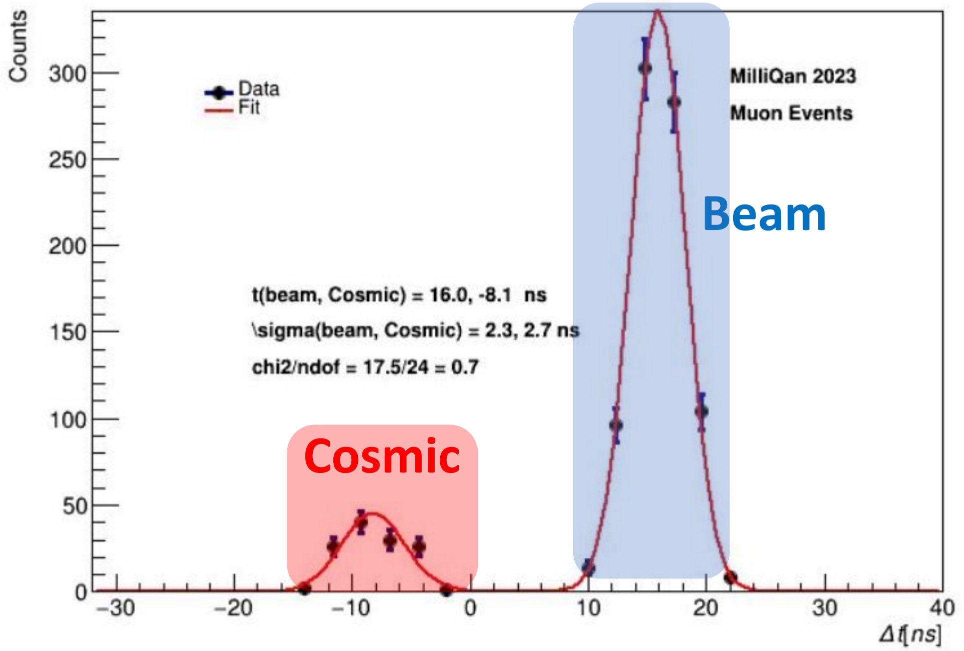


Calibration

THE OHIO STATE UNIVERSITY

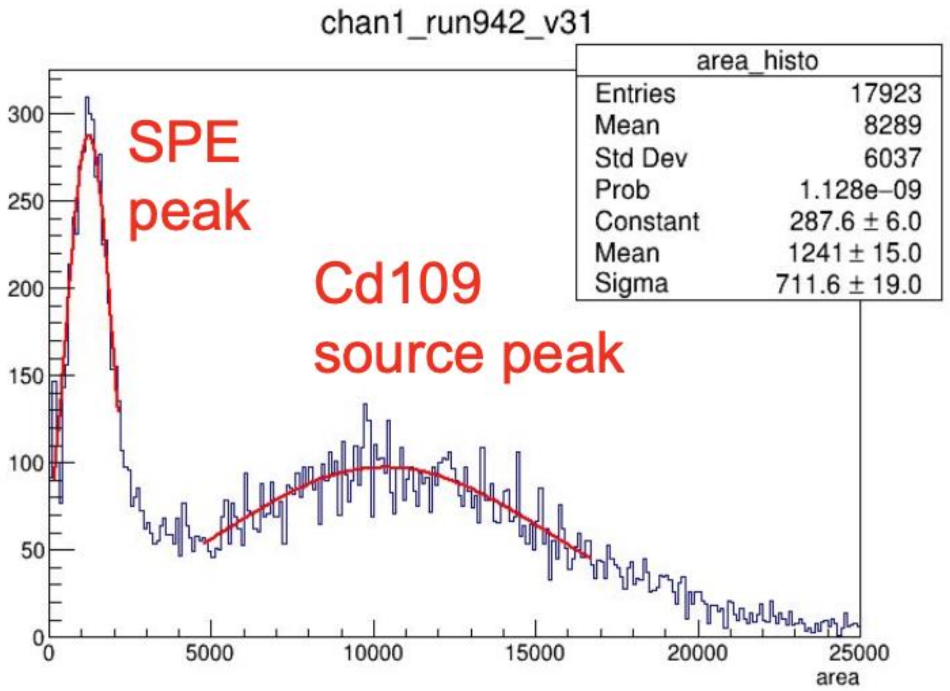
Timing Calibration:

- Calibrate channel timing using beam muons
- Correct for differences in position/cable length



nPE Calibration:

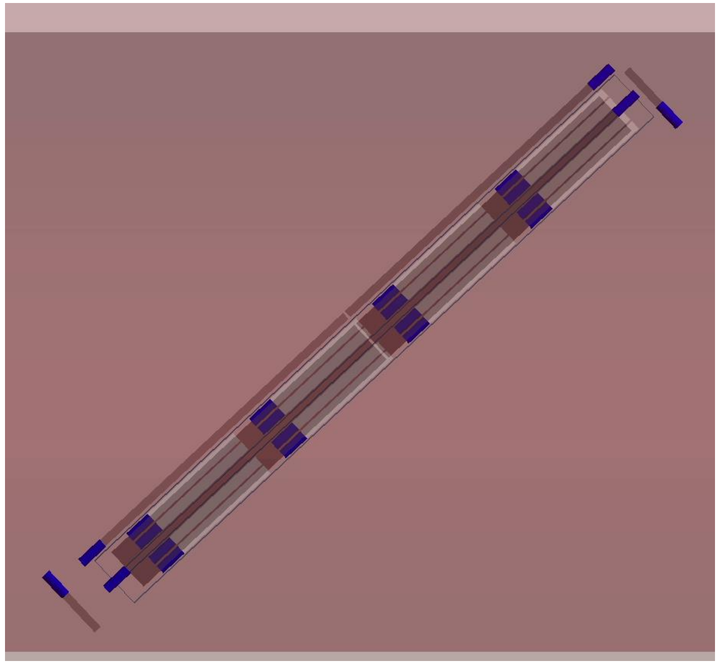
- Calibrate energy of interaction particle -> nPE observed
- Use known source to calibrate (Cd109)



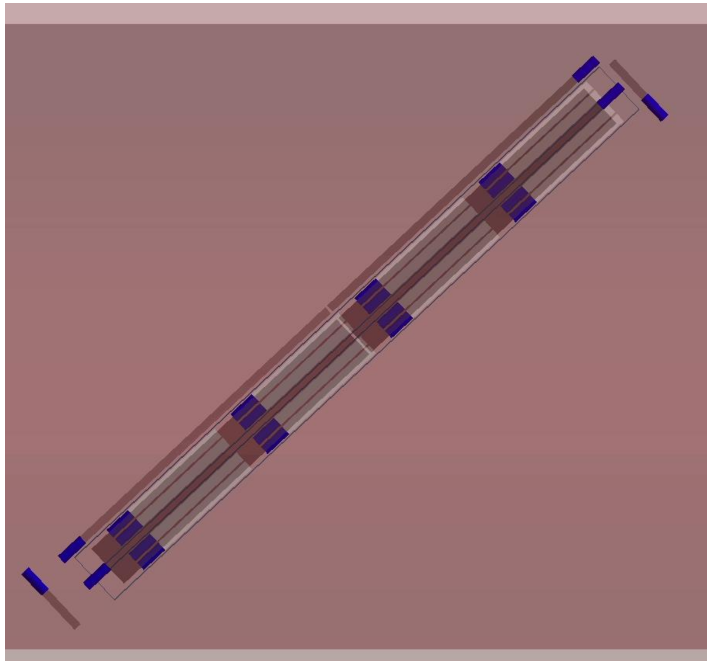
Geant4 Simulation

- milliQan detectors are fully modeled in GEANT4 simulation
- Calibrate each PMT response to in situ version
- Use real pulses as input for simulation (pulse injection)

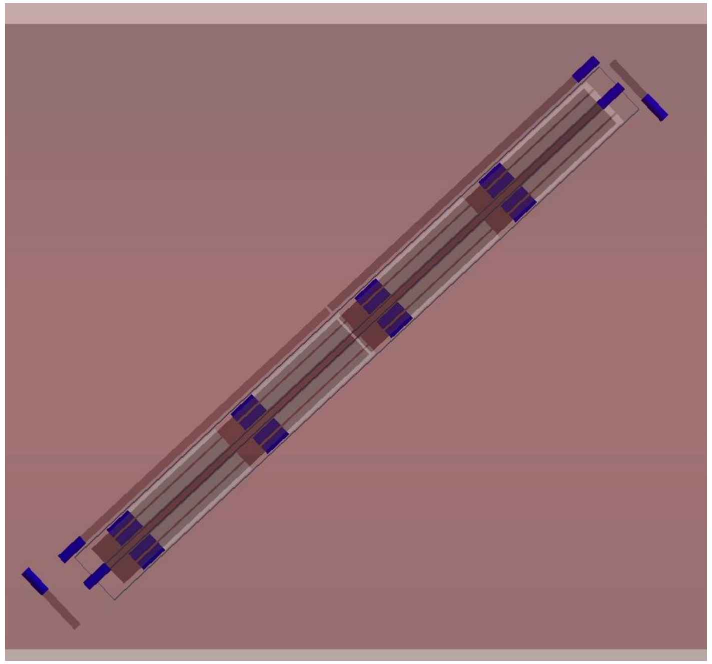
Cosmic Muon



Beam Muon



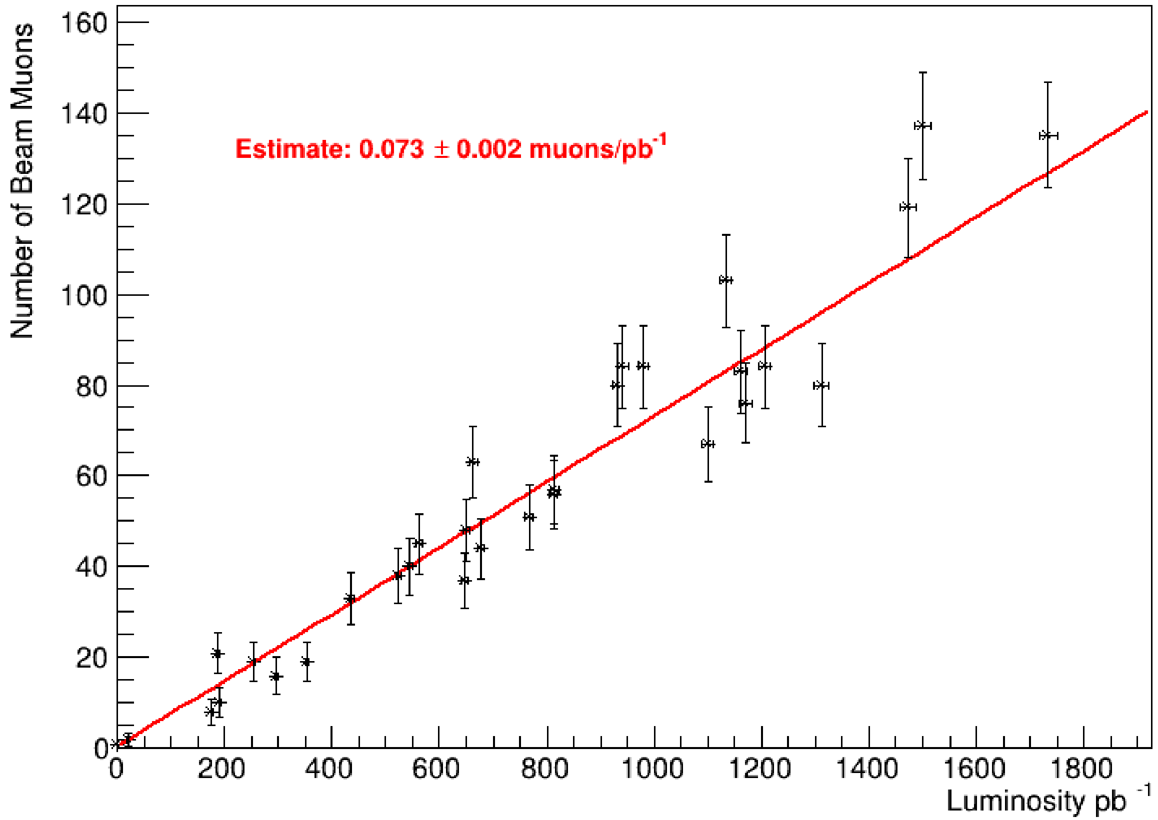
mCP



Simulation Validation

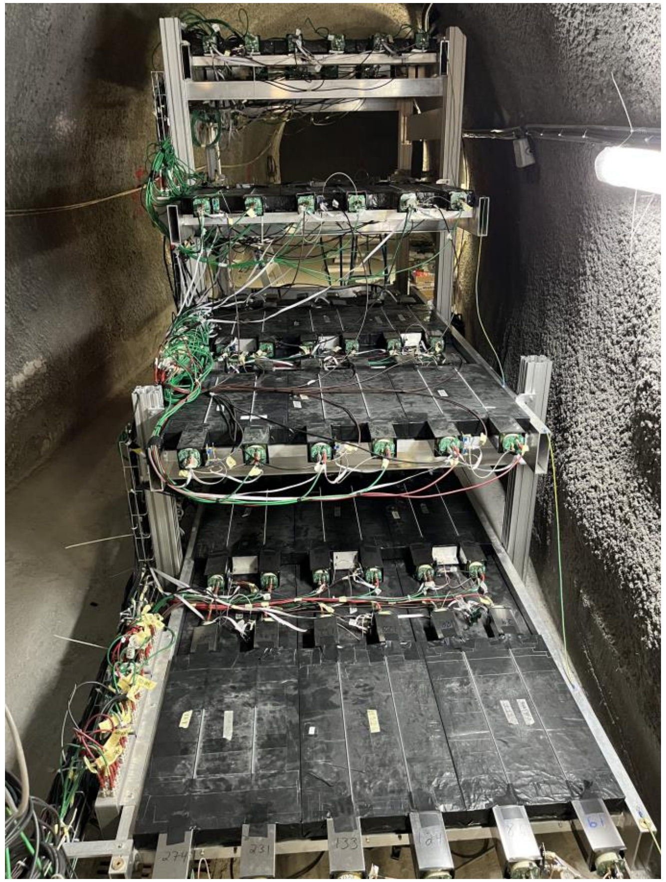
- Validate sim by comparing measured/simulated rate of identified beam muons from CMS IP
  - Similar to demonstrator study
- Identify large hits in every layer of detector
- Preliminary measurement w/ partial data (right)
- Comparison of efficiency in data vs simulation ongoing

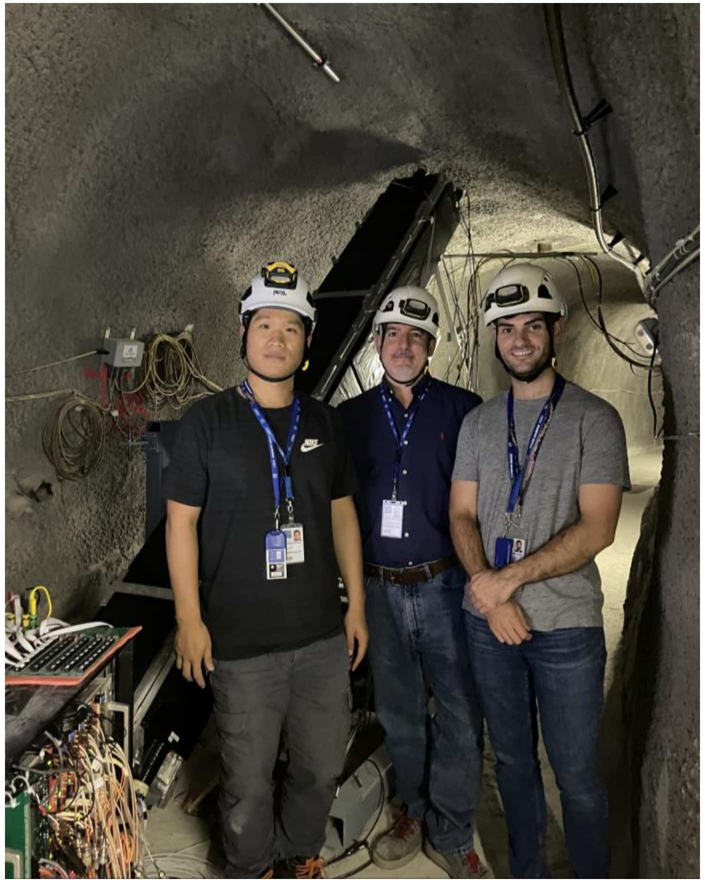
Luminosity vs Identified Beam Muons



Summary

- Bar detector has collected over $72 fb^{-1}$ over 2023/24
- Beginning to analyze the data that we have taken
- Slab detector will be fully built by end of month
- milliQan analyses for bar and slab will follow soon!

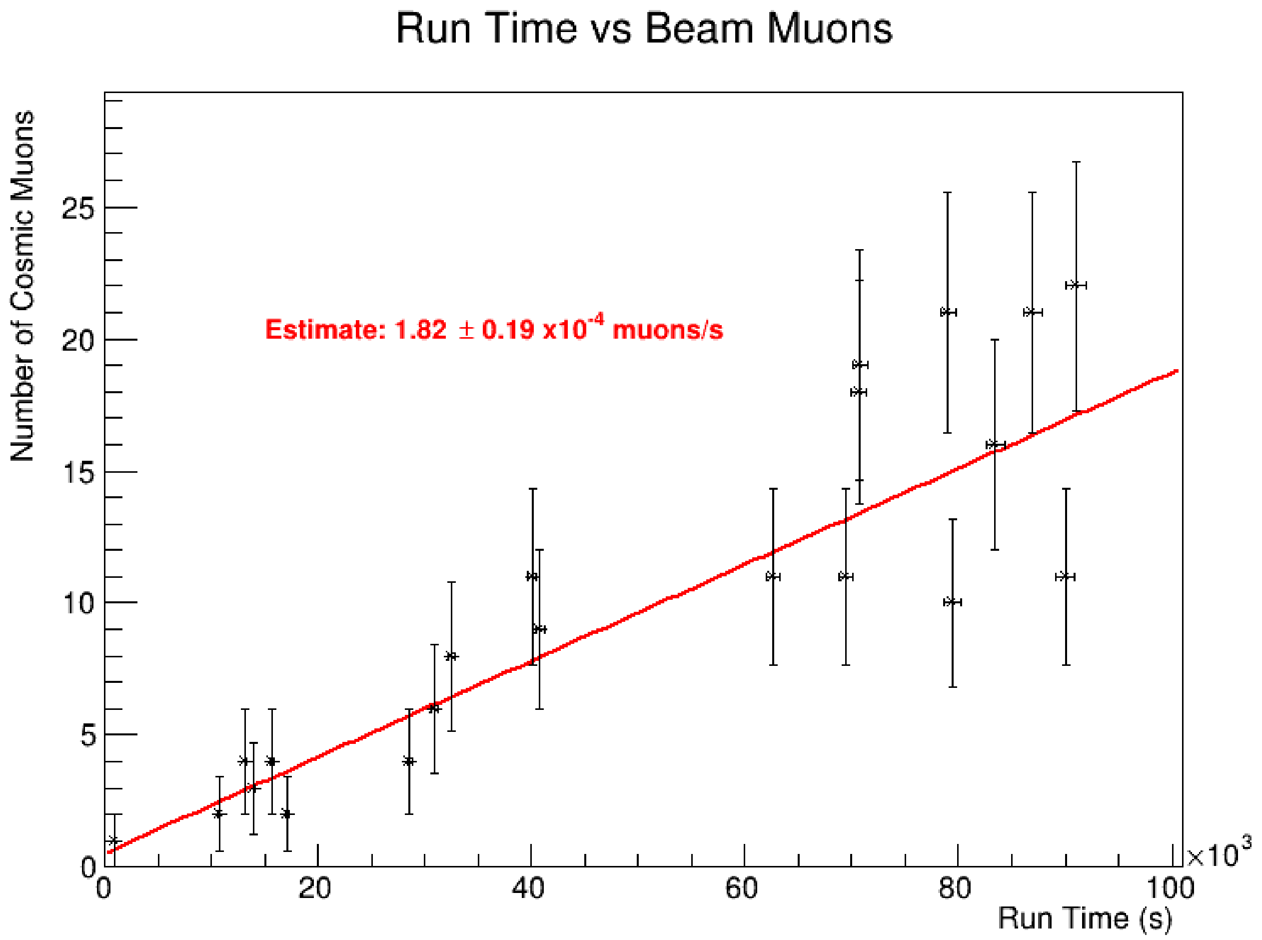




Backup

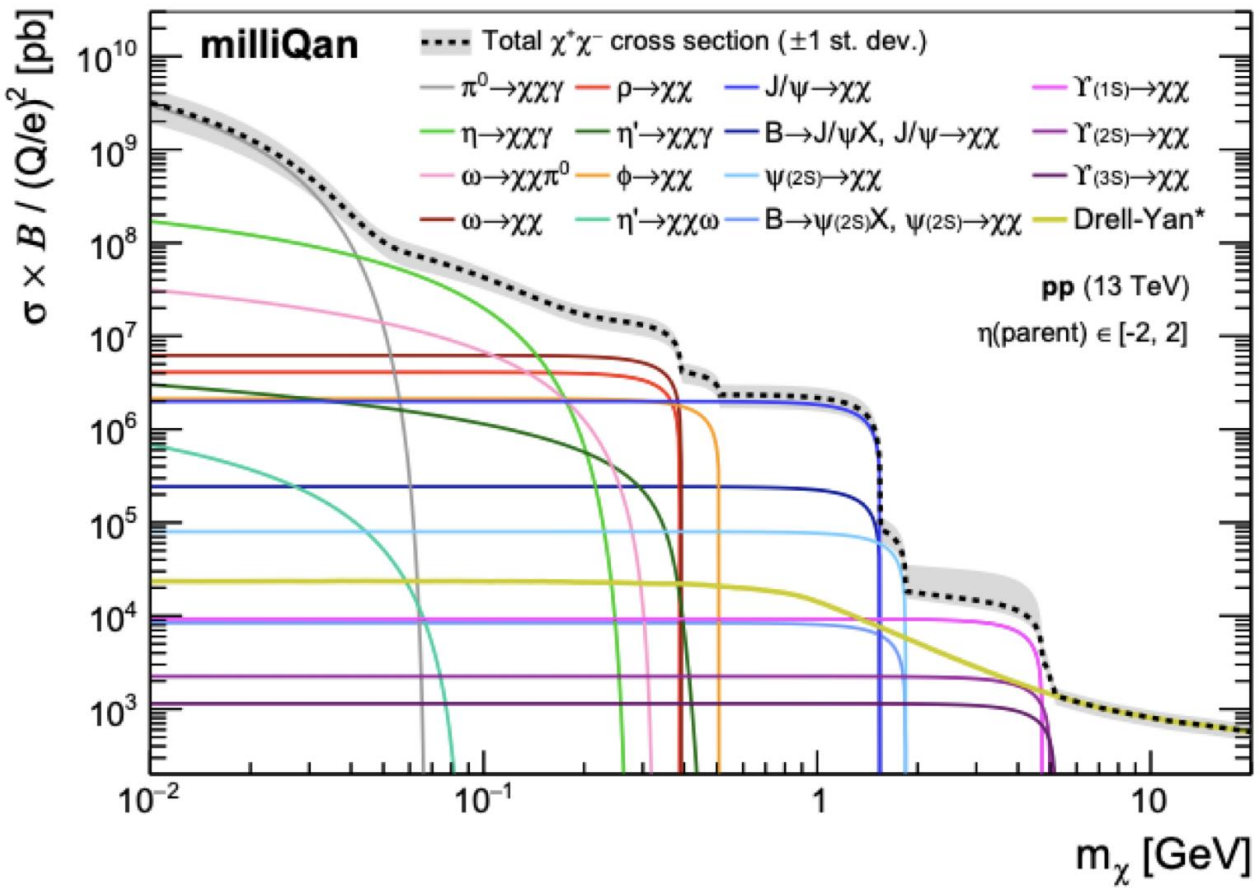
Cosmic Muon Background

- Also measure rate of cosmic muons
- Large hits in 4 layers of bar detector
- Cosmic runs from LHC off used
- Small fraction of runs used (left plot)



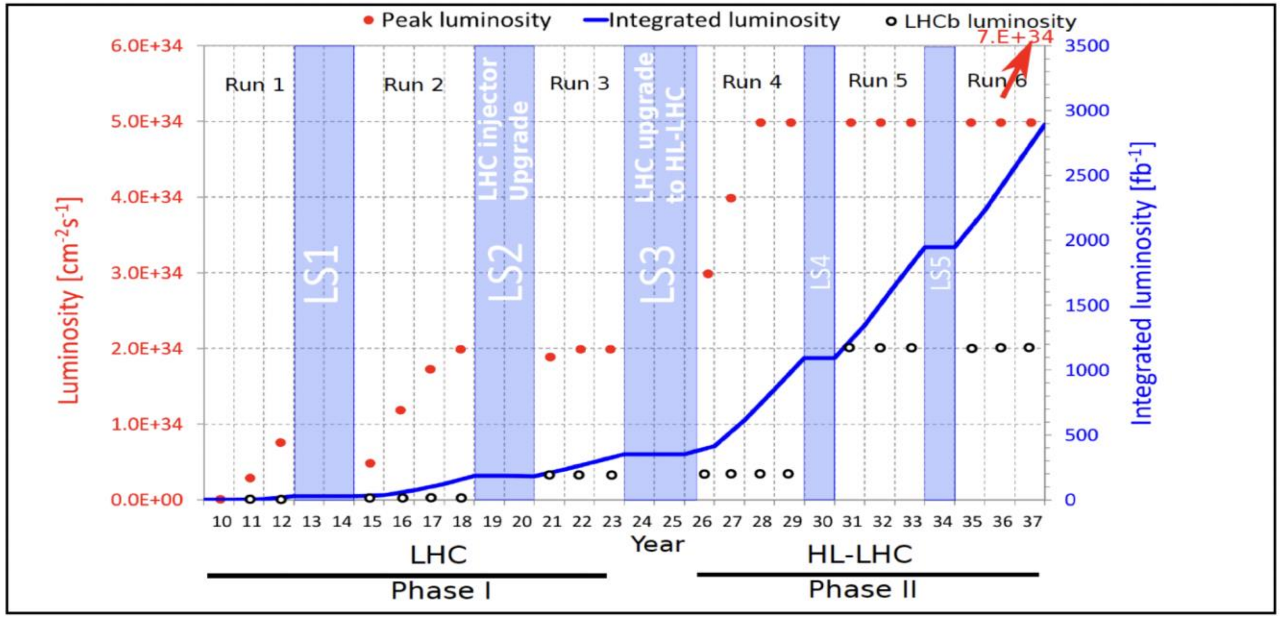
Production in LHC

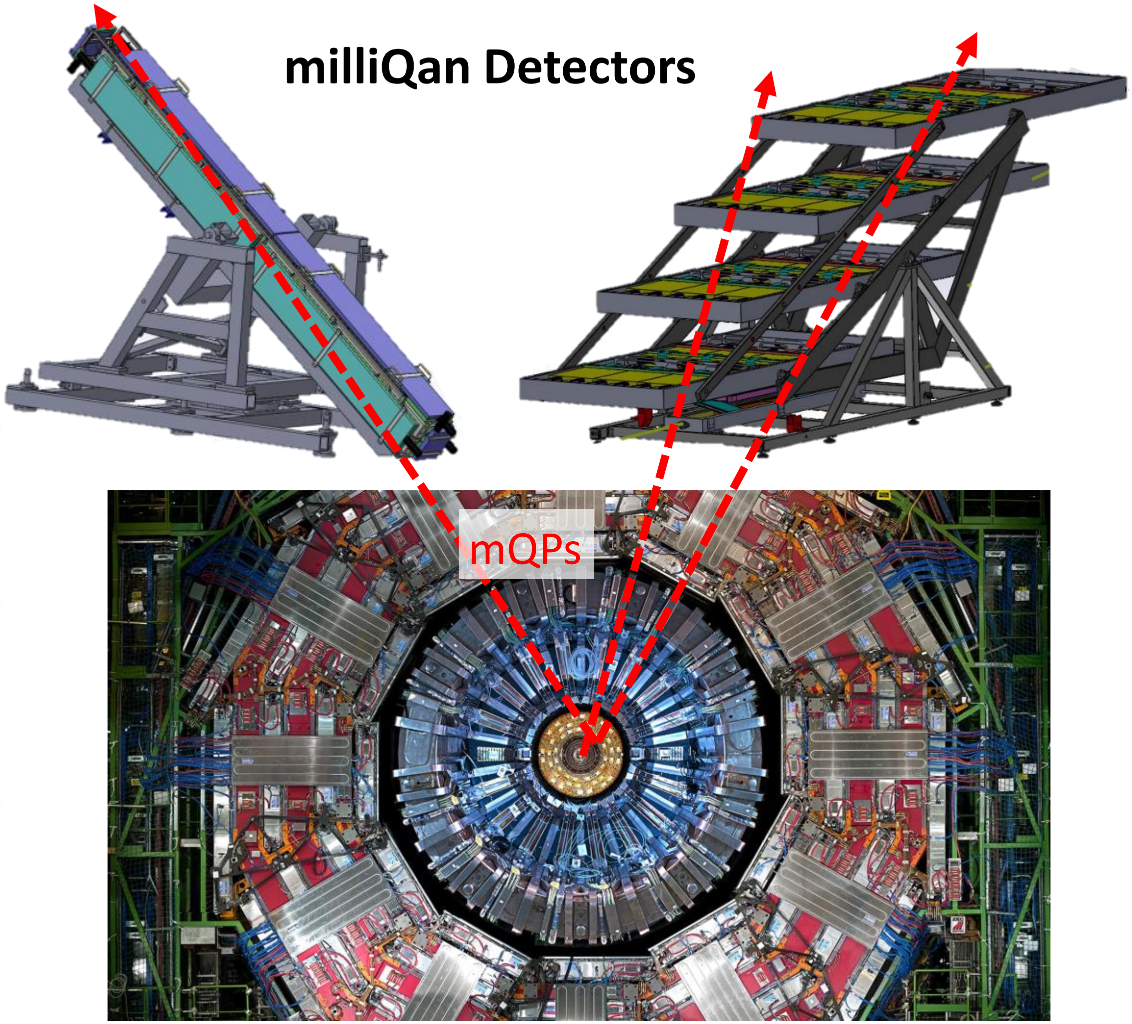
- Production of mQPs in LHC is the same as e+e-
  - Leptonic meson decays
- $Br(x \to q^+q^-) \propto (\frac{q}{e})^2 Br(x \to e^+e^-)$
- Simulate mQPs in pythia
- Propagate through rock/detector with Geant



LHC Run 3

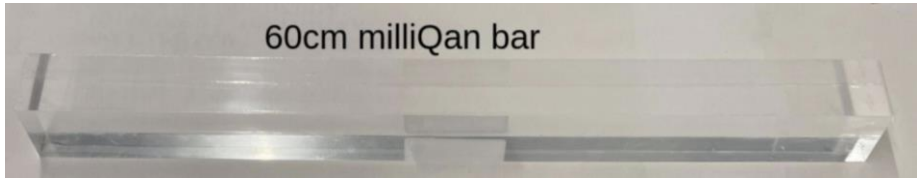
- The LHC is aiming to collect ~300fb^{-1} of data in run 3
- Plan to use milliQan detector to set new limits on production of millicharged particles





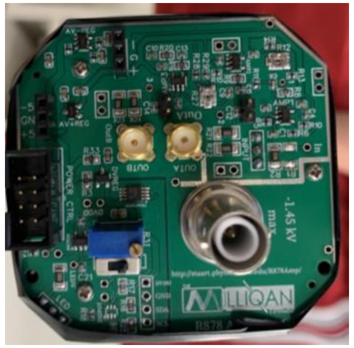
milliQan Detector Overview

- Can use scintillator detectors to detect mCPs:
  1. mCP will create photon(s) in scintillator
  2. Attached PMTs will detect the photon(s)
- milliQan is composed of two scintillator arrays:
  1. Bar Detector (larger version of demonstrator)
  2. Slab Detector (new detector)
- Scintillation is dependent on charge (Q)
  - To probe small charge must be sensitive to O(1) photoelectron (sPE)



Bethe-Bloch

$$-\left\langle \frac{dE}{dx} \right\rangle \sim Q^2$$



Custom PMT amplifier board