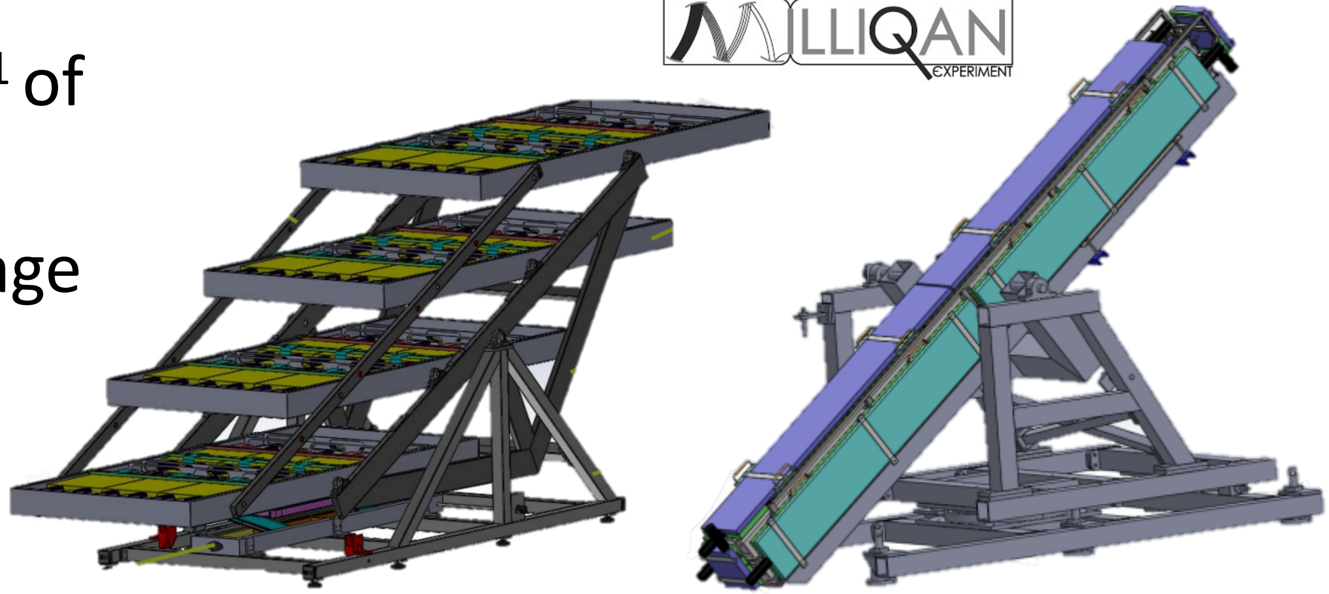
Millicharged Particle Detectors

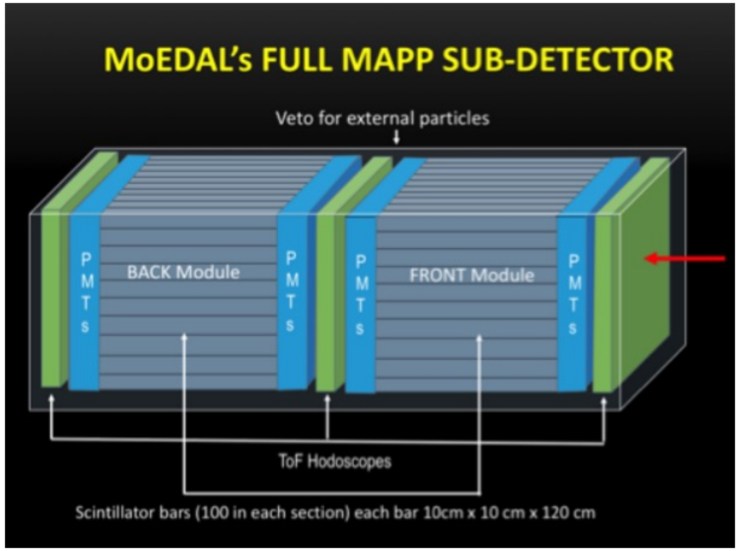
Michael Carrigan for milliQan
- with slides contributed by MoEDAL-MAPP

May 17, 2022 – LHCP 2022

LHC Run 3

- The LHC is aiming to collect ~300fb^{-1} of data in run 3
- Other experiments can take advantage of this increased luminosity!

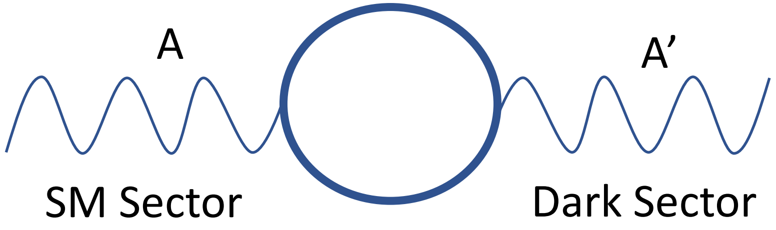




- milliQan and MoEDAL are two experiments located around the LHC far from the IPs
- These detectors take advantage of the collision products and their distance from the IP (shielding from rock) to search for millicharged particles

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 $\epsilon = \kappa e' cos\theta_w / e$

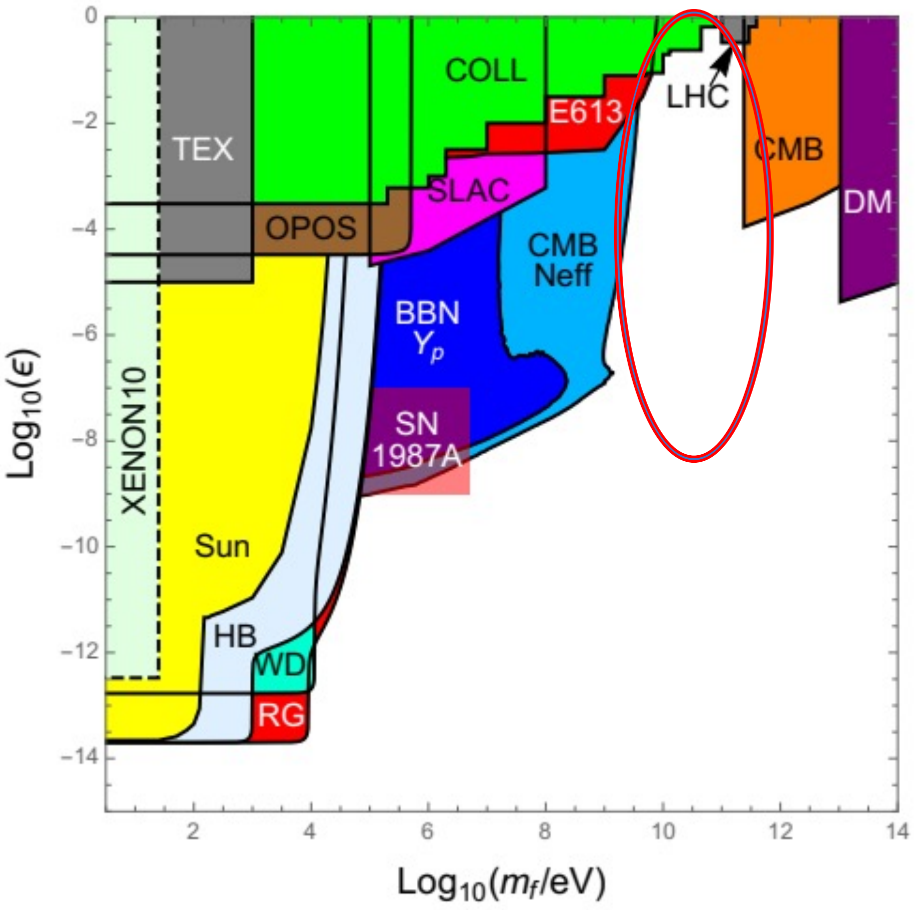


$$\mathcal{L} = \mathcal{L}_{SM} - \frac{1}{4} A'_{\nu\mu} A'^{\mu\nu} + i\bar{\psi}(\not{\partial} + ie'\not{A}' + iM_{mCP})\psi - \frac{\kappa}{2} A'_{\mu\nu} B^{\mu\nu}$$

Dark Photon Term | Dark Fermion | Kinetic Mixing Term

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

Previous Searches

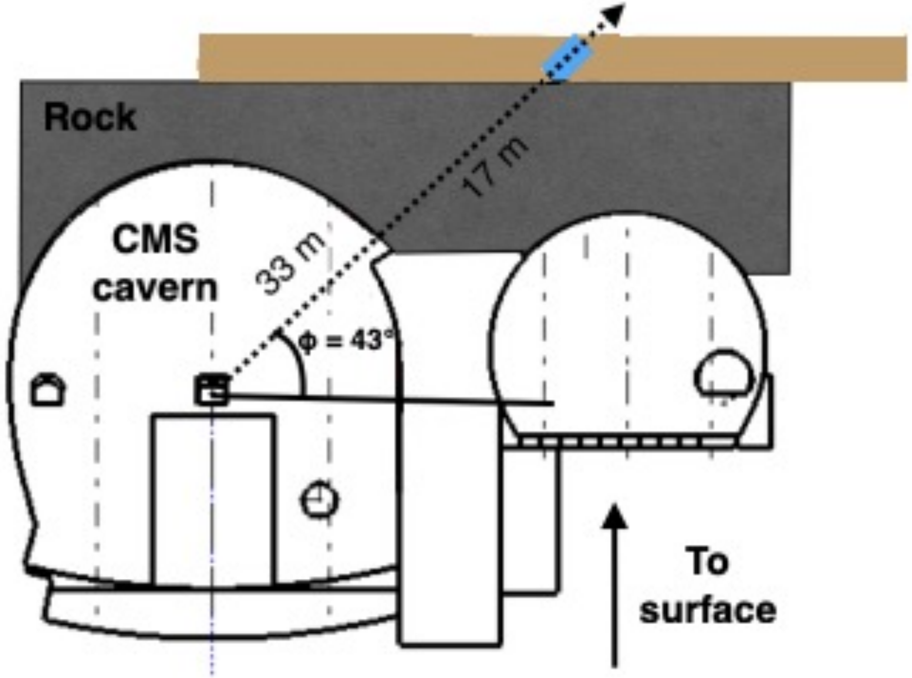


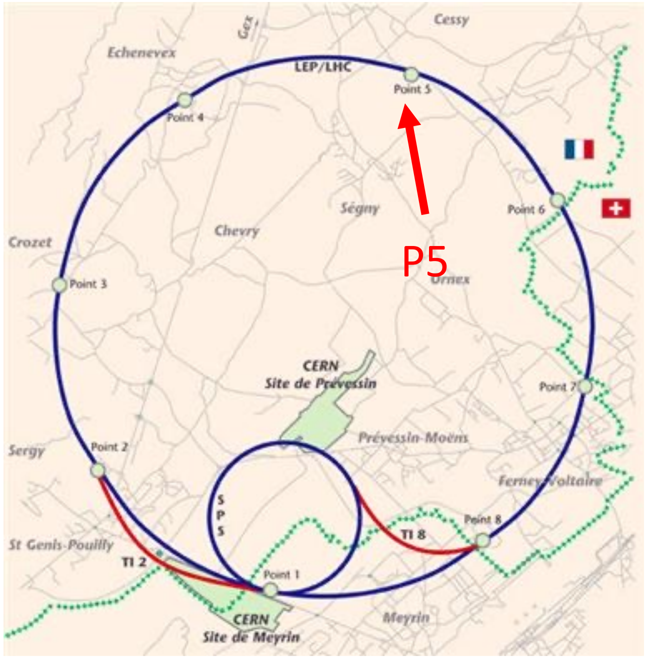
- Limits on charge and mass of millicharged particles set by numerous experiments
- Large gap for masses O(10^{-1}-10^{2})GeV
- Some limits set by:
  - Cosmic microwave background and CMB N_{eff}
  - SLAC MilliQ experiment (similar to milliQan and MAPP)
  - CMS searches for fractional charges
- This gap is targeted by both millQan and MoEDAL-MAPP

milliQan

milliQan Detector Location

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

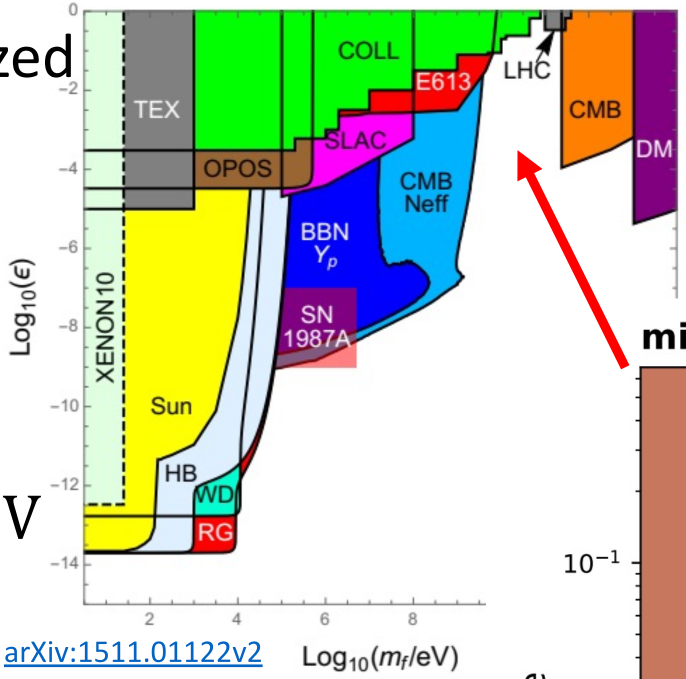




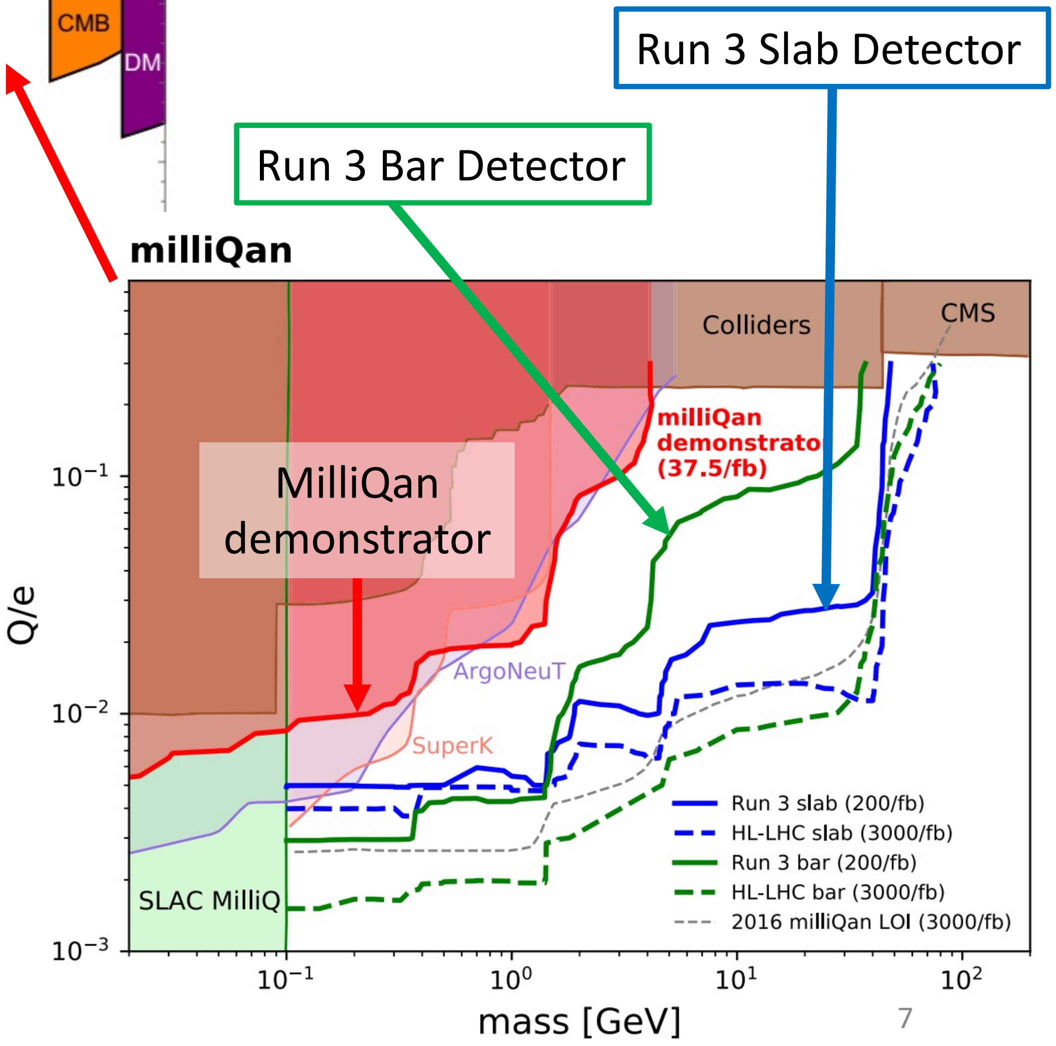
drainage gallery

Improving milliQan Sensitivity

- Millicharged particle parameterized by mass and charge of particle
- Previous experiments unable to probe this area
- milliQan detector aims to probe undetected phase space
  - $10^{-1} GeV < M_{mCP} < 10^{2}\text{GeV}$
  - $10^{-3} < \frac{Q}{e} < 10$



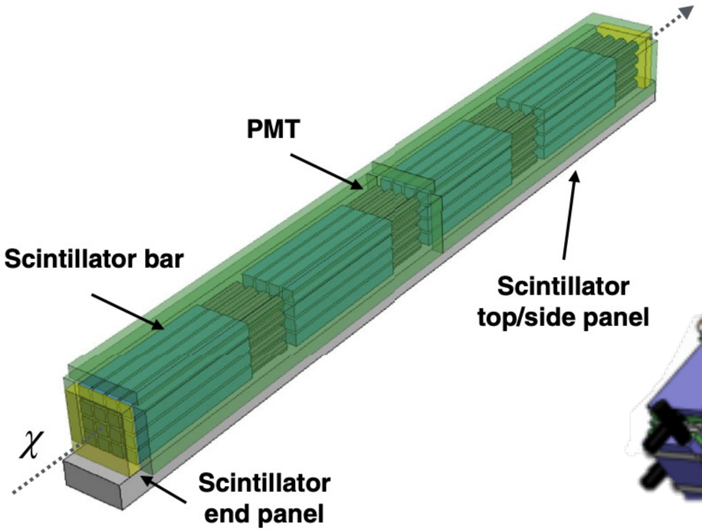
arXiv:1511.01122v2



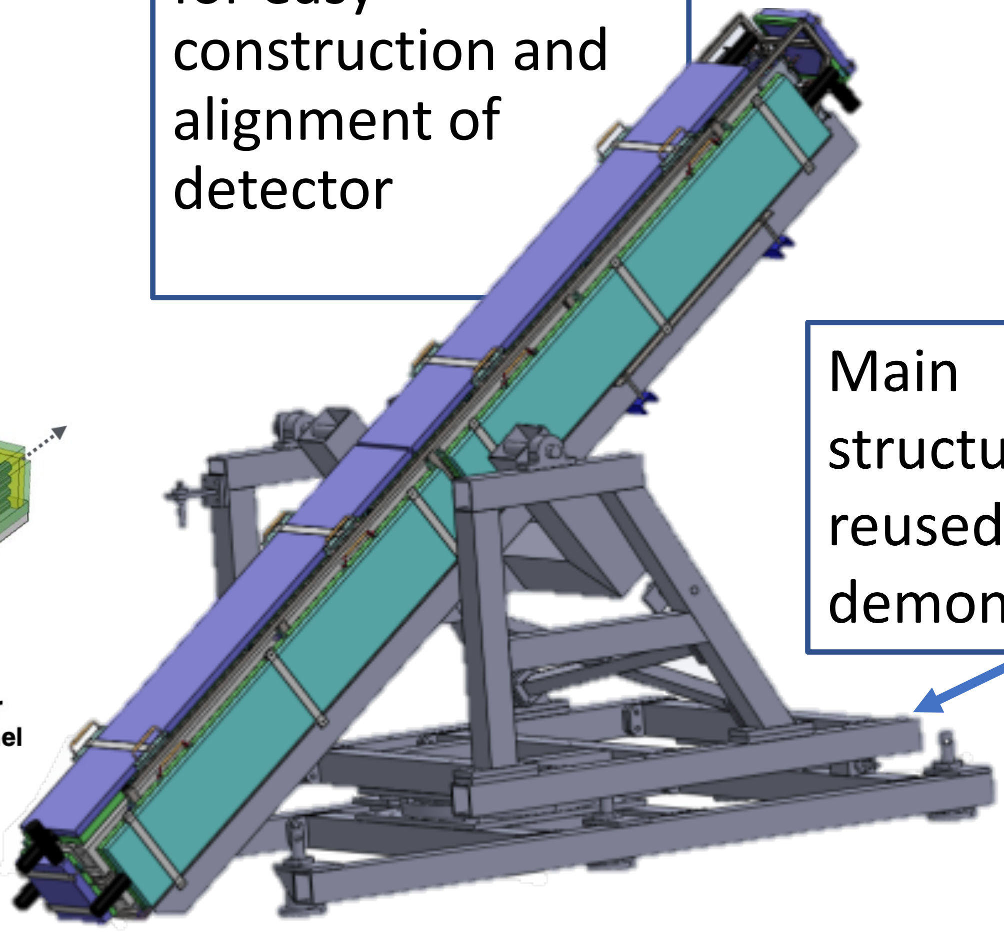
- In Spring of 2021 published paper with run 3 design and updated sensitivity
- Exclusion limits for bar and slab detector from this paper are shown (Phys. Rev. D **104**, 032002)

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 sPEs
  - Etc…



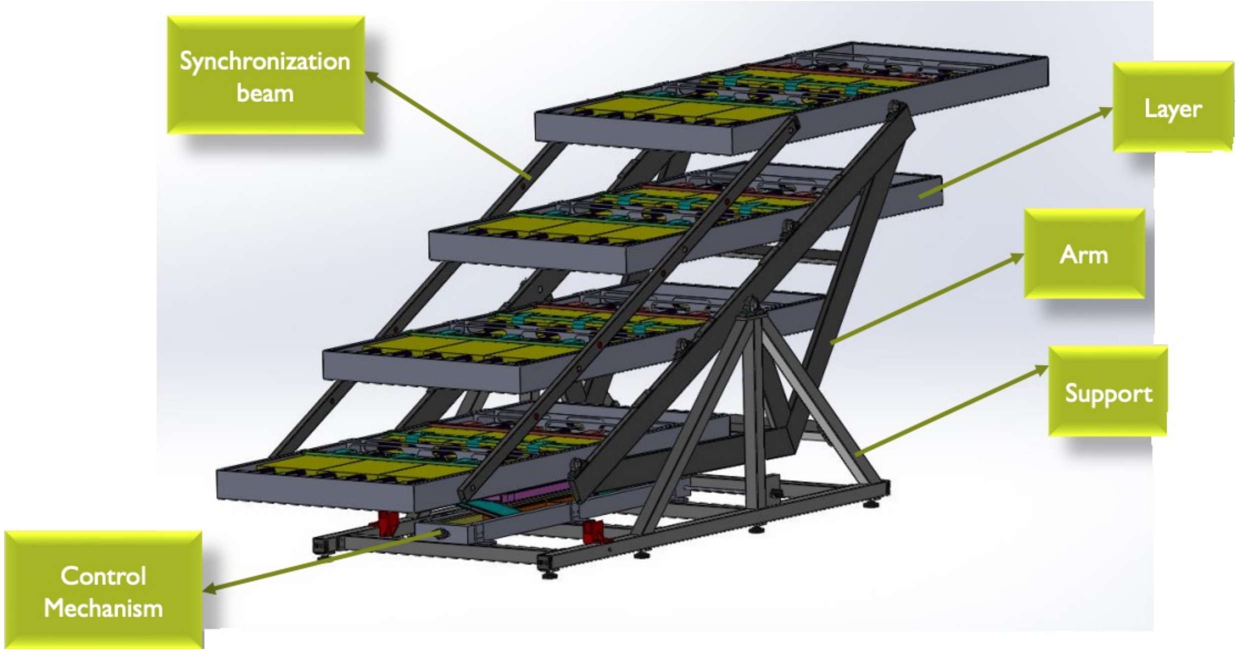
Lever arm allows for easy construction and alignment of detector

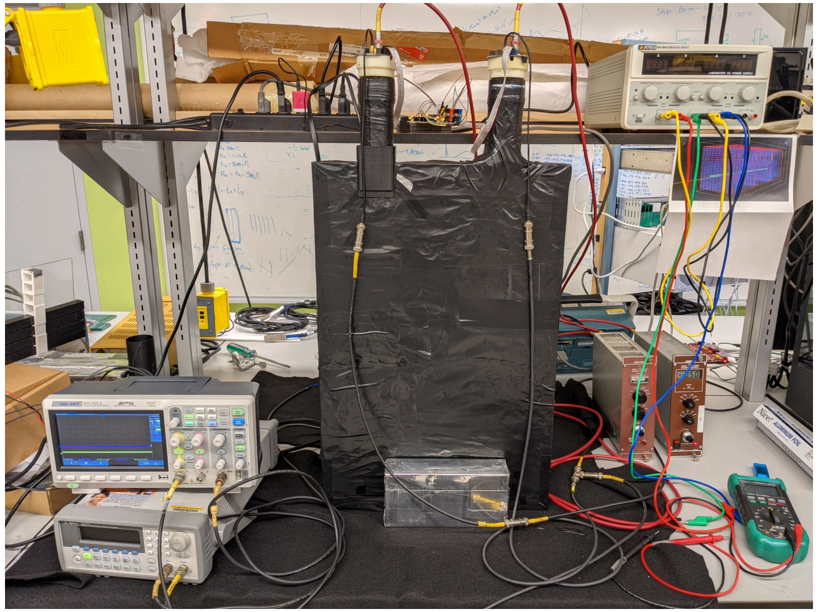


Main structure reused from demonstrator

milliQan Slab Detector

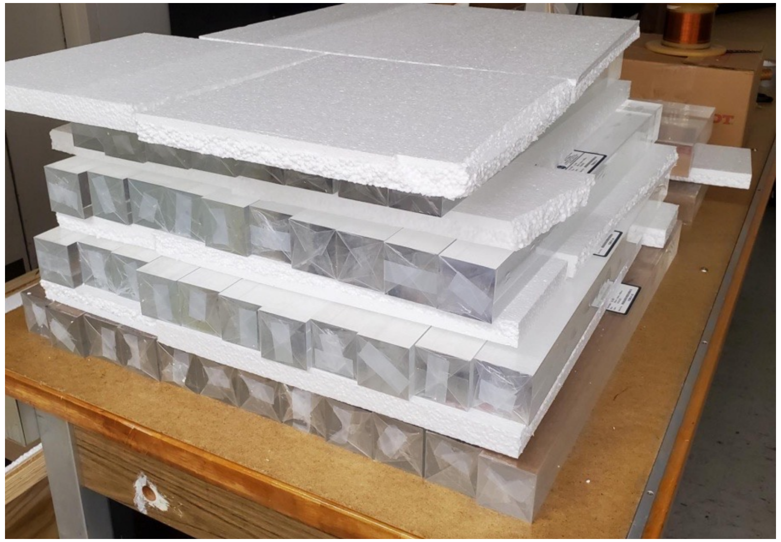
- Run 3 detector also includes a separate slab detector comprised of four layers of 12 scintillator slabs (40cm x 60cm x 5cm each)
- Larger area increases signal acceptance at higher masses ($M_{mCP} \gtrsim 1.4GeV$)
- 4 PMTs per slab to increase collection efficiency





Bar/Slab Module Construction

- Scintillator wrapped and tested at UCSB, U. Chicago, NYU, and University of Nebraska
- Bar and slab detectors currently being built at CERN



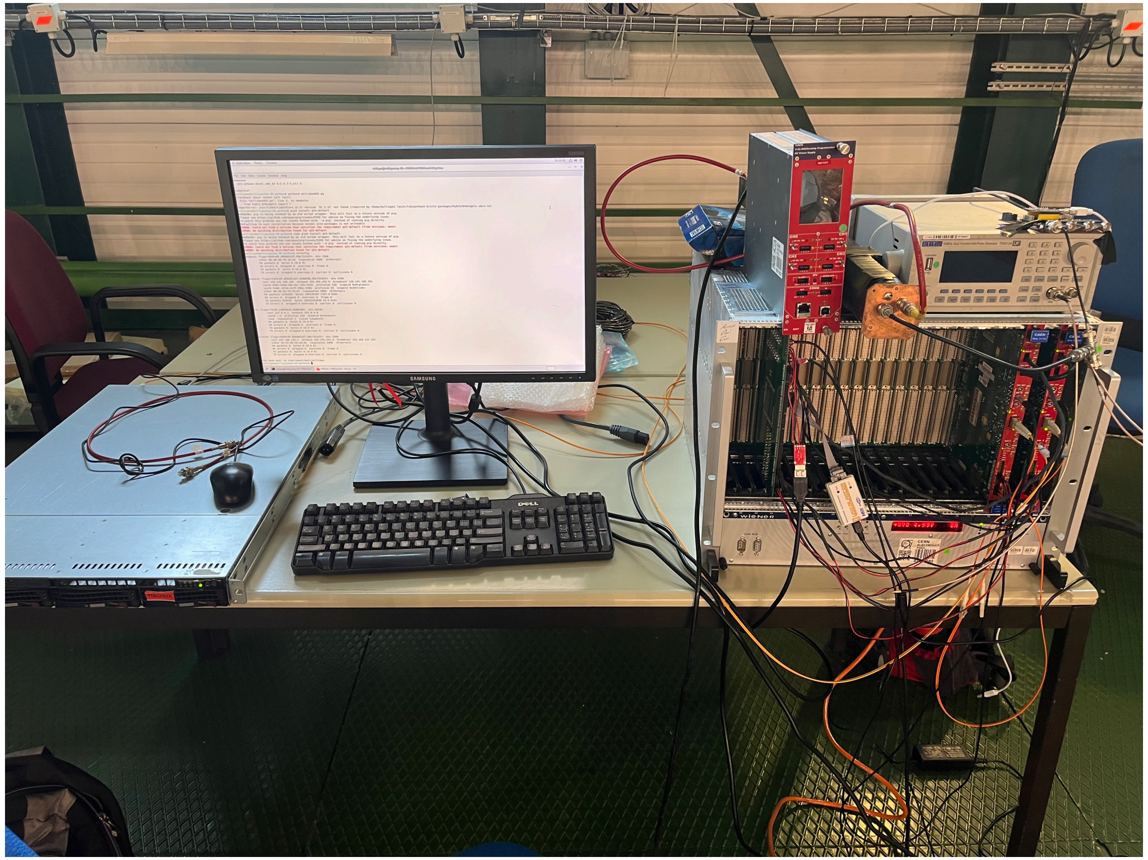
- Custom PMT amplifier bases are designed and built at UCSB
- Everything now shipping to CERN

Demonstrator Decommissioning

- To prepare for installation of the run 3 bar detector we are now decommissioning the demonstrator
- Old equipment is being brought to surface

CERN Lab Testing

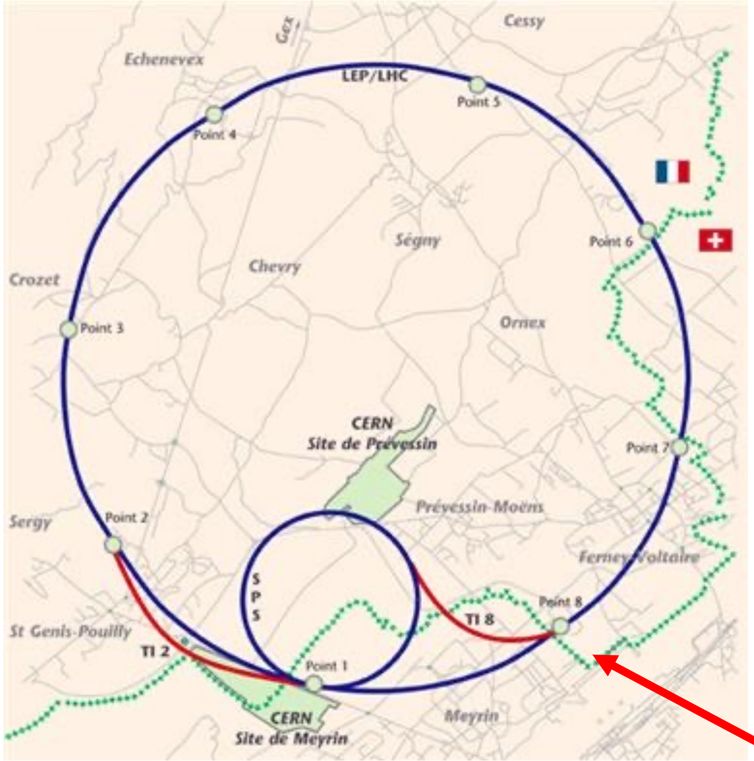
- Lab in the CMS assembly hall is used to test and calibrate our electronics, scintillators, PMTs, etc…



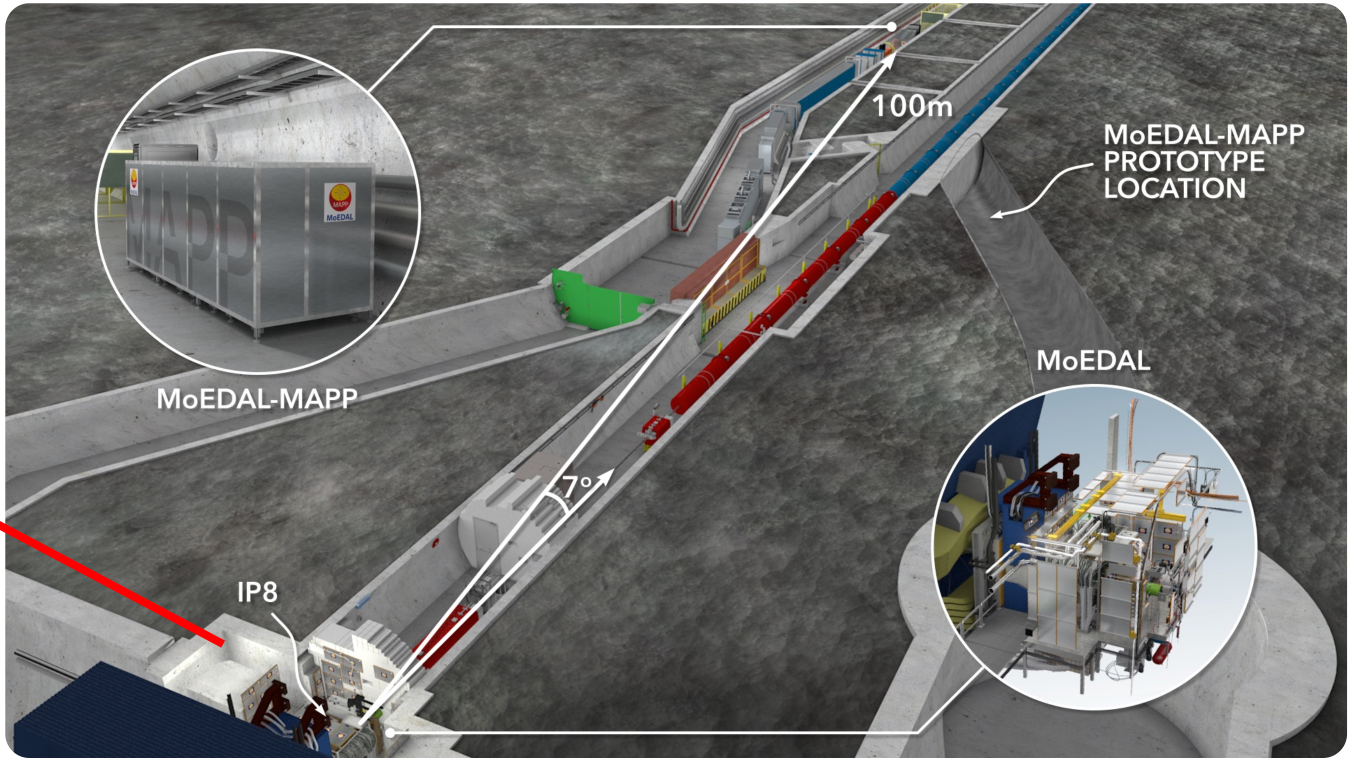
MoEDAL-MAPP

MoEDAL’s Apparatus for detecting Penetrating Particles

MAPP Detector Location



- MAPP detector will be in UA83
- ~100m away from MoEDAL (near LHCb)

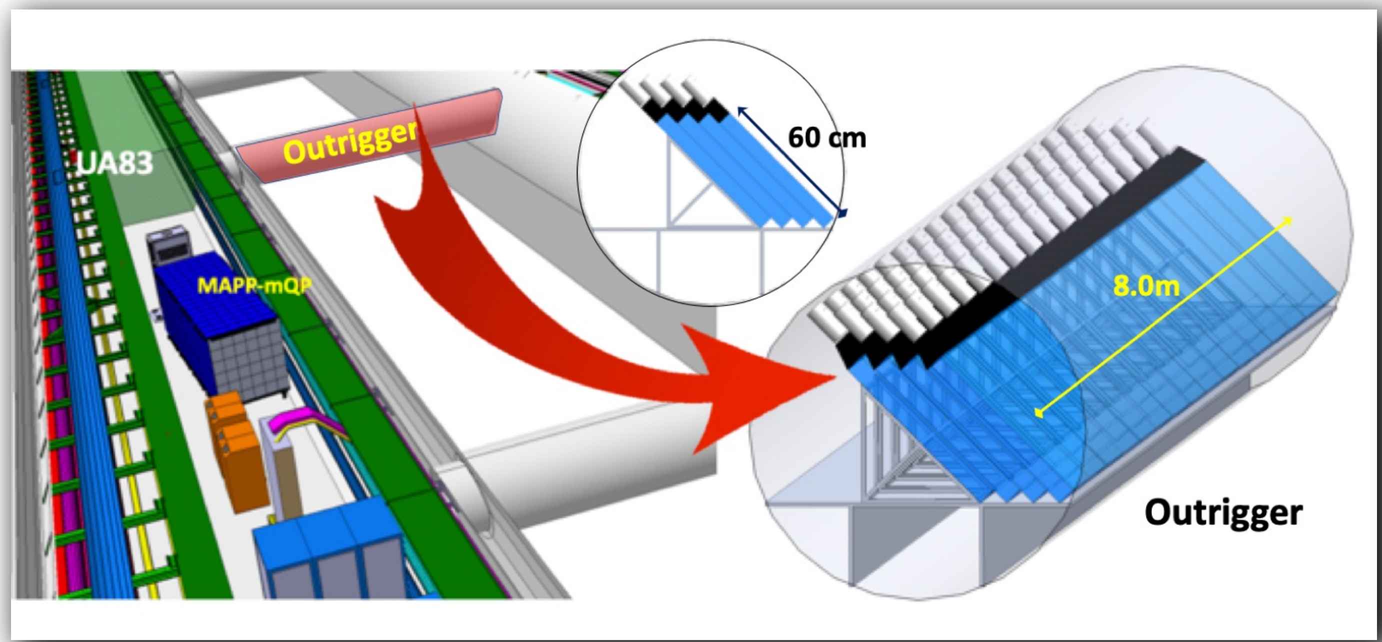


- Slightly different location from the prototype

MAPP Phase-1 Installation

- As of Feb 25, 2022 the MAPP detector has installed:
  - Support frame for scintillator bars
  - Fraction of the scintillator bars
  - Power connection
  - Ethernet connection
  - Fiber optic cable with LHC clock signal

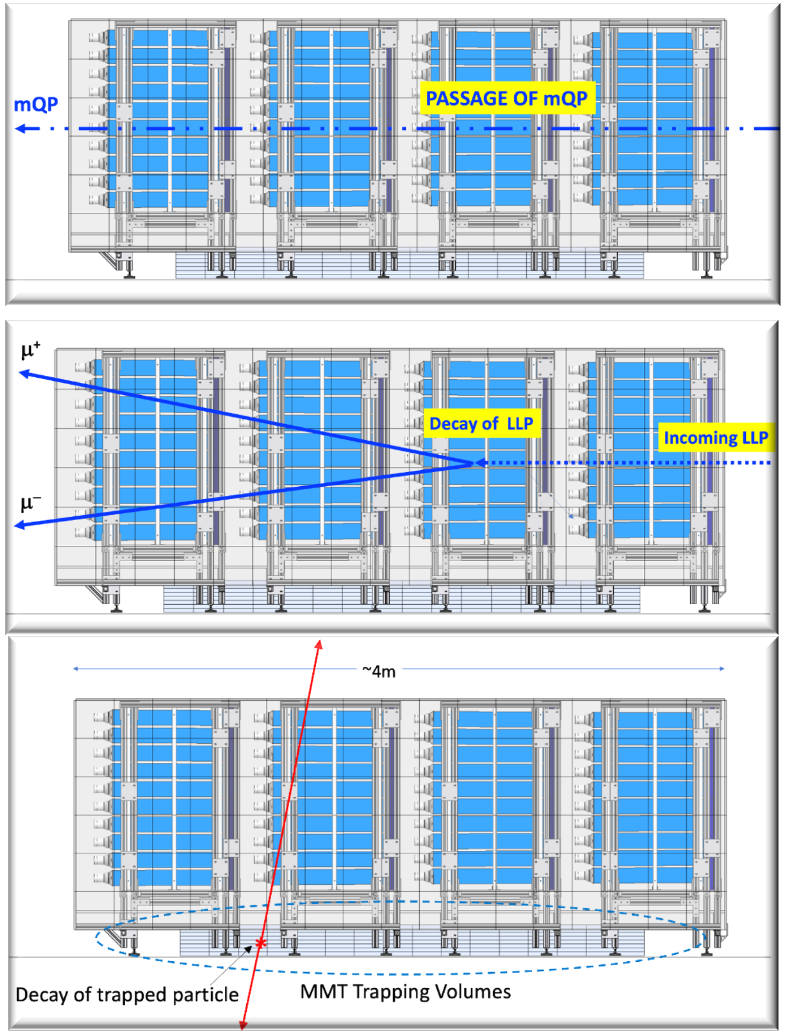
MAPP Outrigger



- MAPP outrigger designed to improve acceptance of mCPs at higher fractional charges
- Scintillator "blocks" with size 50cm x 60cm x 5cm attached to PMTs

- Coincidence of 4 hits defines a mCP track
- Outrigger detector area is 4.8 m^2 – between ~ 1.5 & 6.5 deg. and 105m from the IP
- Plans to install after the MAPP Run3 detector

MAPP Particle Detection



Millicharged particle detection

Neutral LLP Detection

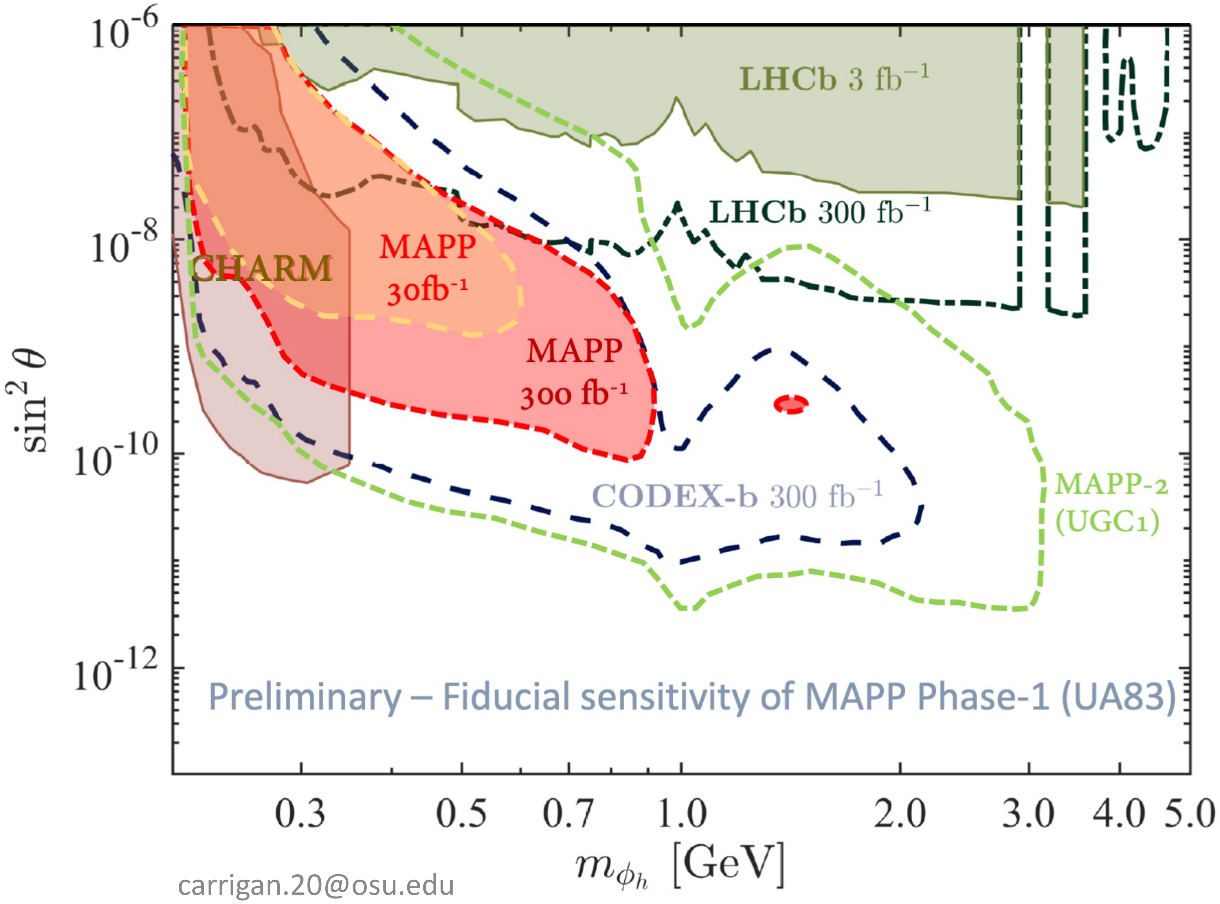
Charged LLP Detection (In conjunction with MoEDAL)

- MAPP detector will look for:
  - Millicharged particles
  - Neutral LLPs
  - Charged LLPs
- MAPP will monitor MoEDAL trapping detector
- Trapping detector exposed for 1y then moved below MAPP
- Sensitive to particles with lifetimes O(10y)

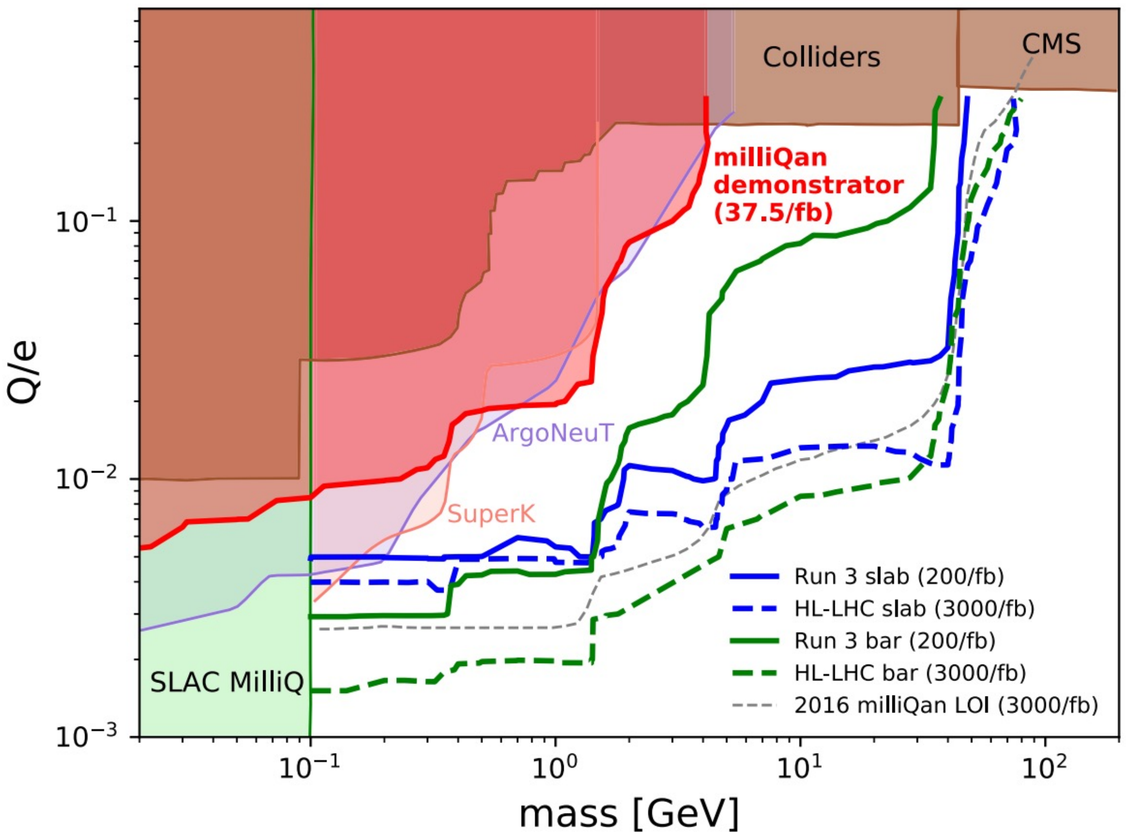
Summary

milliQan and MAPP plan to significantly improve current limits with Run3 data!

MoEDAL-MAPP Dark Higgs Long Lived Particle



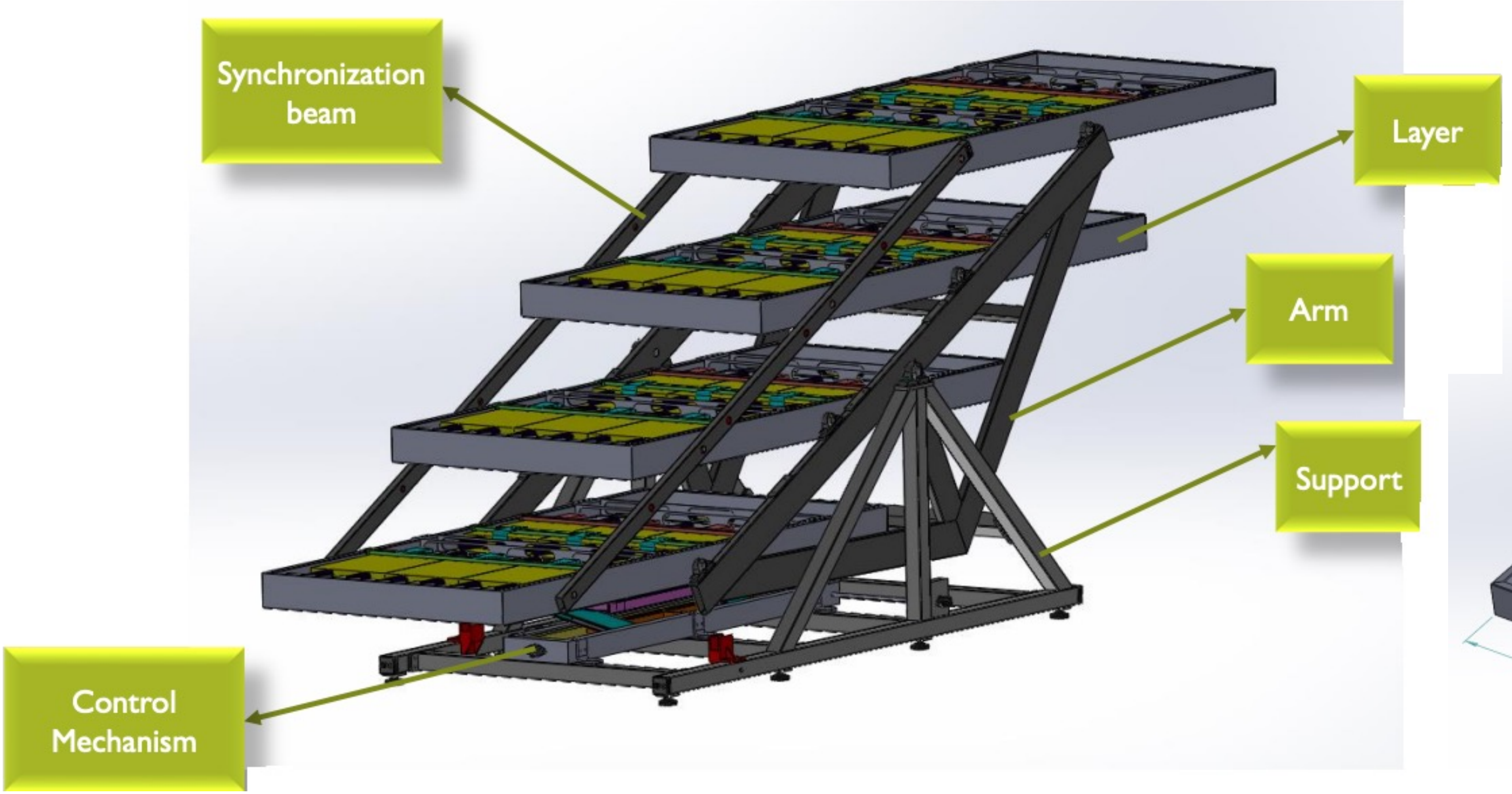
milliQan Millicharged Particle

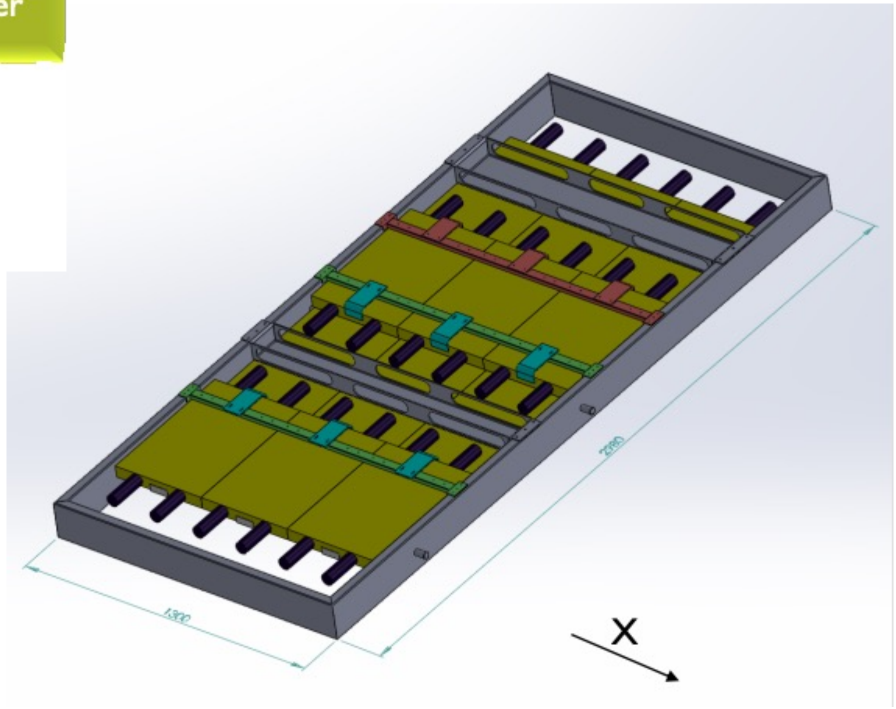


Backup

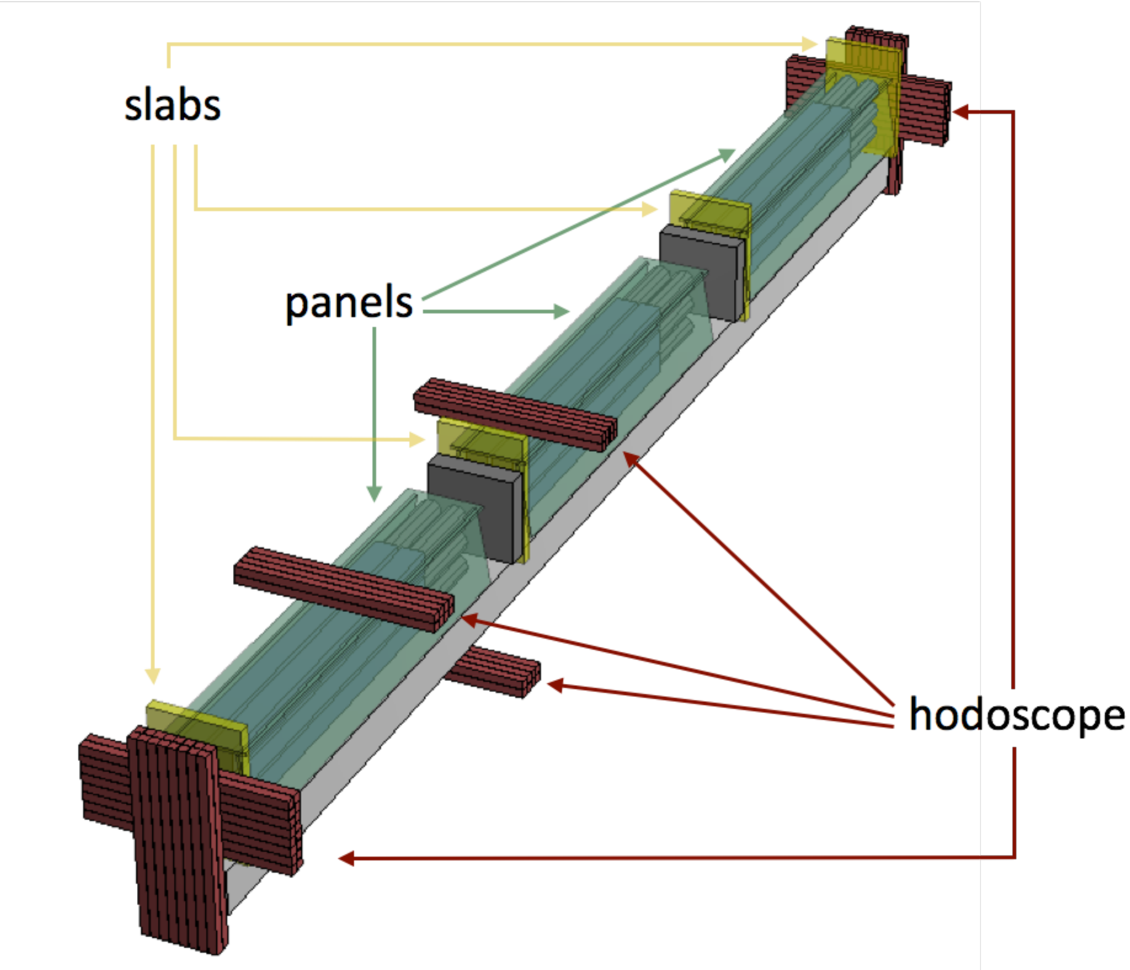
Slab Detector Mechanics

- Slab detector is being built in parallel with bar detector





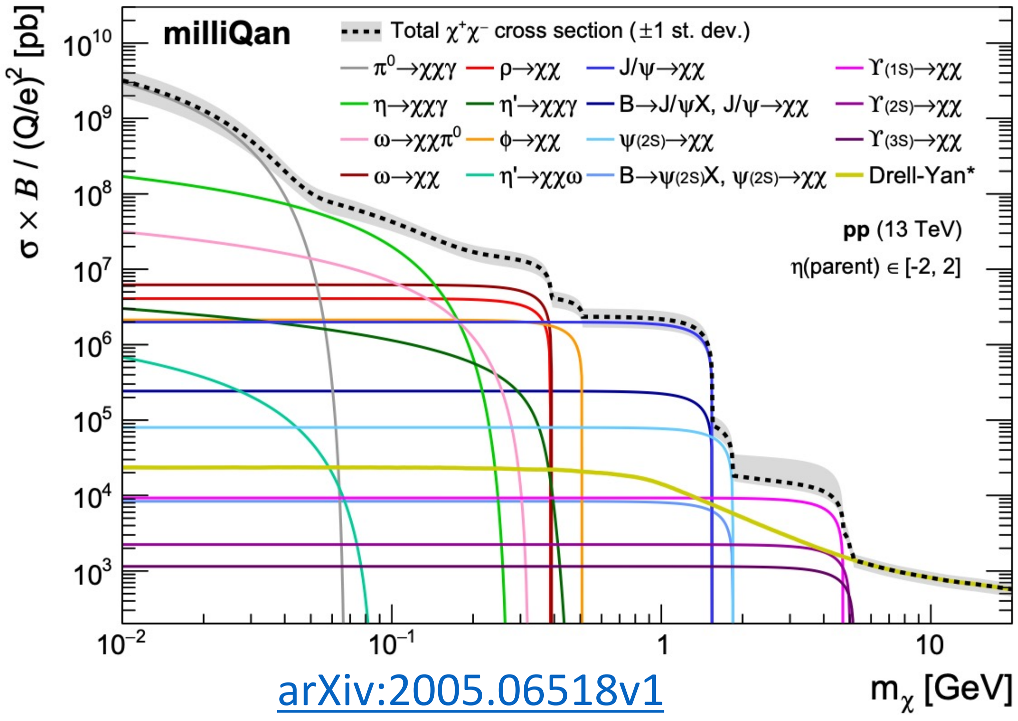
milliQan Demonstrator



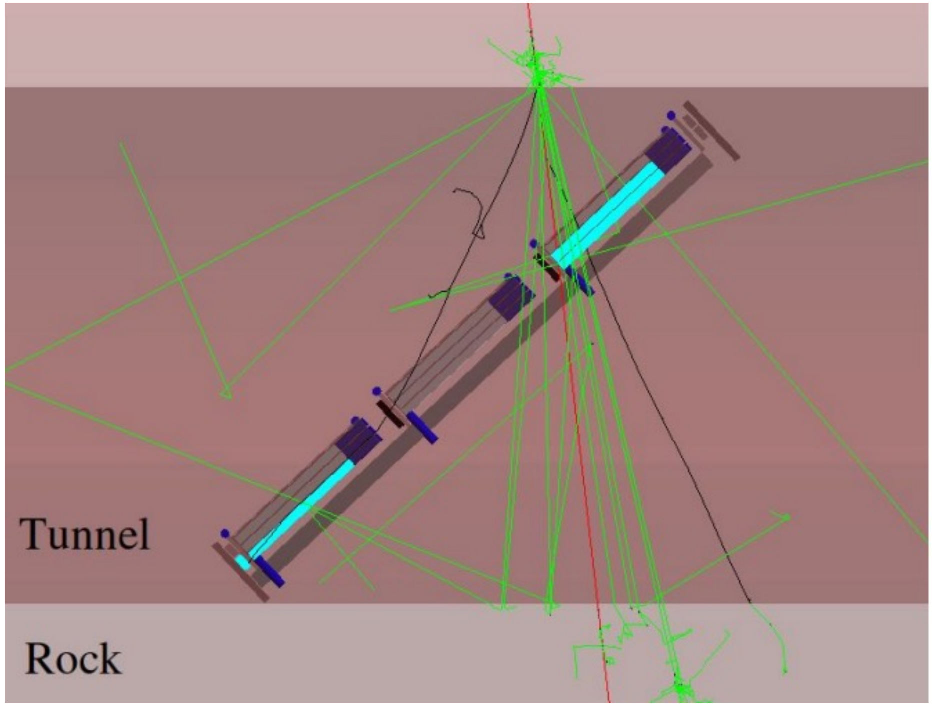
- Demonstrator was a 1% detector to test overall design
- 3 layers of a 3x2 array of scintillator bars attached to PMTs
- Scintillator "slabs" and lead plates between layers to help define pointing path and stop beam muons
- Scintillator panels surrounding bars to help veto cosmics
- Hodoscope in front and back to help with pointing path and timing

Signal/Background Simulation

- Signal mCPs are simulated through many different processes and propagated through CMS B-field and the 17m of rock



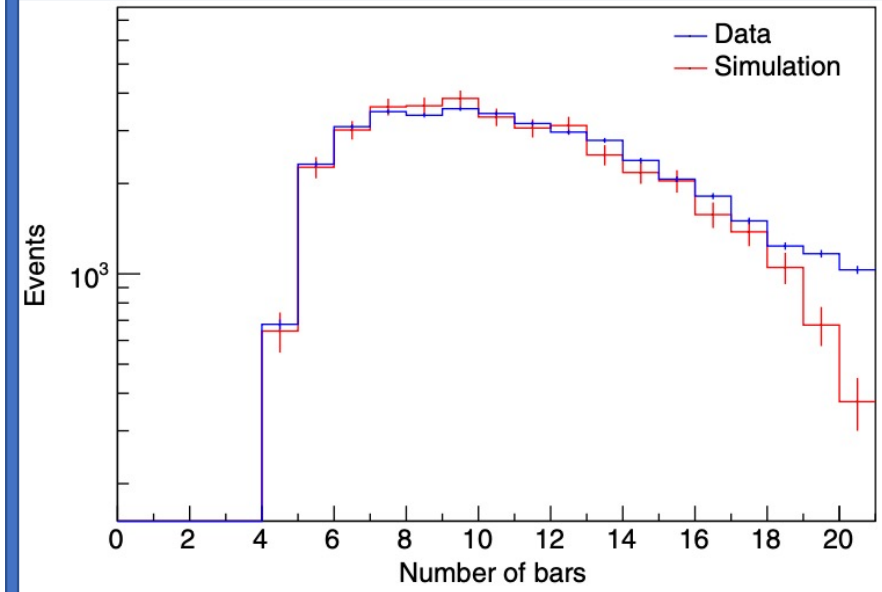
arXiv:2005.06518v1



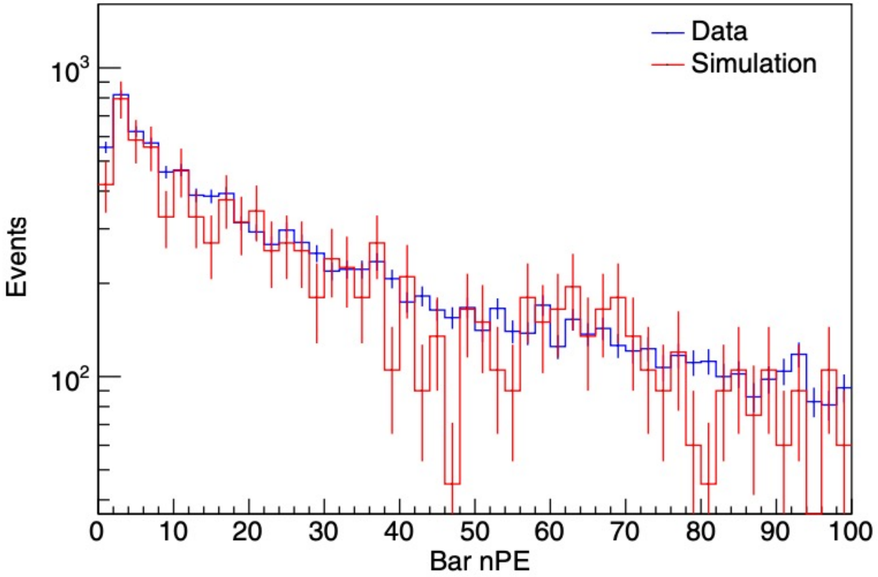
- The detector is then modeled using Geant4 and validated using data from the demonstrator

Background Validation

- Data was collected during beam off using run 2 demonstrator aligned horizontally to allow addition of two bars to simulate run 3 bar detector
- This data was then compared with simulation of cosmic muons to validate simulation



Number of bars detecting a pulse in a cosmis event in data (blue) and simulation (red)



nPE in a pulse for cosmic events in data (blue)and simulation (red)

Bar Detector Shower Background

- One of the two main background for the experiment is the shower background from cosmic muons
- The below is the bar detector signal selection and the estimated bar detector background after each cut

Selection	Run 3 $200\ fb^{-1}$	HL-LHC $3000\ fb^{-1}$	
≥ 1 per layer	8.1×10^5	8.2×10^7	mCPs must have one hit per layer and no more
$= 1$ per layer	6.0×10^3	1.1×10^4	
Cosmic panel veto	1.1×10^3	3.1×10^3	Cosmics coming from above/sides and beam muons coming from IP are vetoed
Beam muon panel veto	780	3.0×10^3	
Four in line	0.19	2.9×10^{-4}	mCPs will travel straight through 4 layers
Max n_{pe}/Min n_{pe} < 10	0.061	9.1×10^{-5}	mCPs leave the same energy deposit in each layer
-15 ns $< \Delta t_{max} <$ 15 ns	0.012	2.0×10^{-5}	mCP must travel in small time window

Slab Detector Shower Background

The cuts for the slab detector follow the cuts of the bar detector with two main differences:

1. The slab detector has no veto panels
   → Only the self-veto on muons is used (max/min nPE)
2. The distance between layers is larger, and for low charge mCPs a pulse is only seen when travelling below c
   → A larger timing window is allowed
   $$15ns < \Delta t_{max} < 45ns$$

Selection	Run 3
≥ 1 per layer	2.0×10^7
$= 1$ per layer	4.8×10^6
Muon veto	2.6×10^5
Four in line	76
Max n_{pe}/Min $n_{pe} < 10$	23
-15 ns $< \Delta t_{max} <$ 15 ns	7.1
15 ns $< \Delta t_{max} <$ 45 ns	1.4

Background Estimate
Run 3 ($200fb^{-1}$)

Timing Window

$\|\Delta t_{max}\| < 15ns$	$15ns < \Delta t_{max} < 45ns$
7.1 ± 3.9 events	1.4 ± 0.8 events

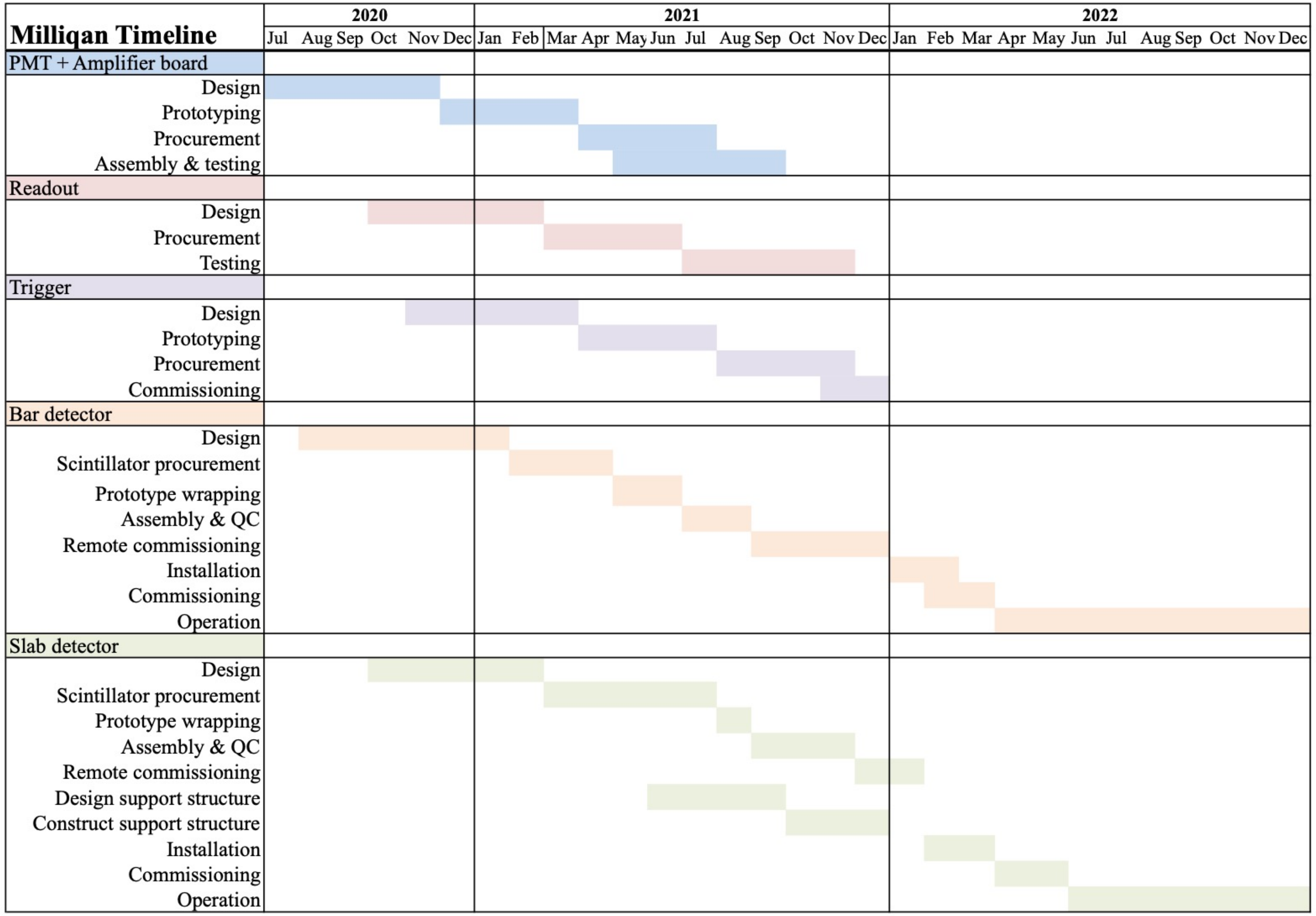
PMT Dark Rate Background

- The PMT dark pulse rate has been measured at 2kHz during the running of the demonstrator
- The estimated run time of the detectors during run 3 is $1.5\times10^{7}s$
- Requiring 15ns maximum time difference between pulses this gives 0.0032 events per signal-like path
- The bar detector has 16 signal-like paths, and the slab detector has 12

Run 3 Dark Pulse Background Estimate

Bar Detector	Slab Detector
0.05 events	0.03 events $(\lvert\Delta t_{max}\rvert < 15ns)$
	0.7 events $(15ns < \Delta t_{max} < 45ns)$

Timeline



- Well underway on assembly and quality control for bar and slab detector
- On schedule for installation of both detectors at the beginning of 2022
- In time to operate at the start of run 3!