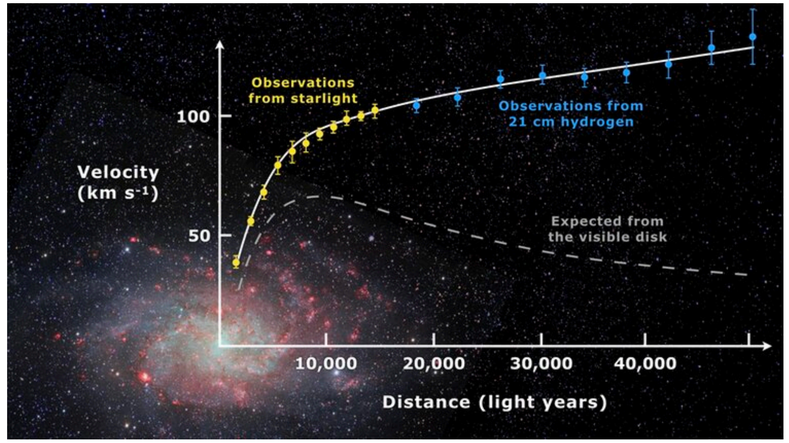
MilliQan and MoEDAL-MAPP status and prospects

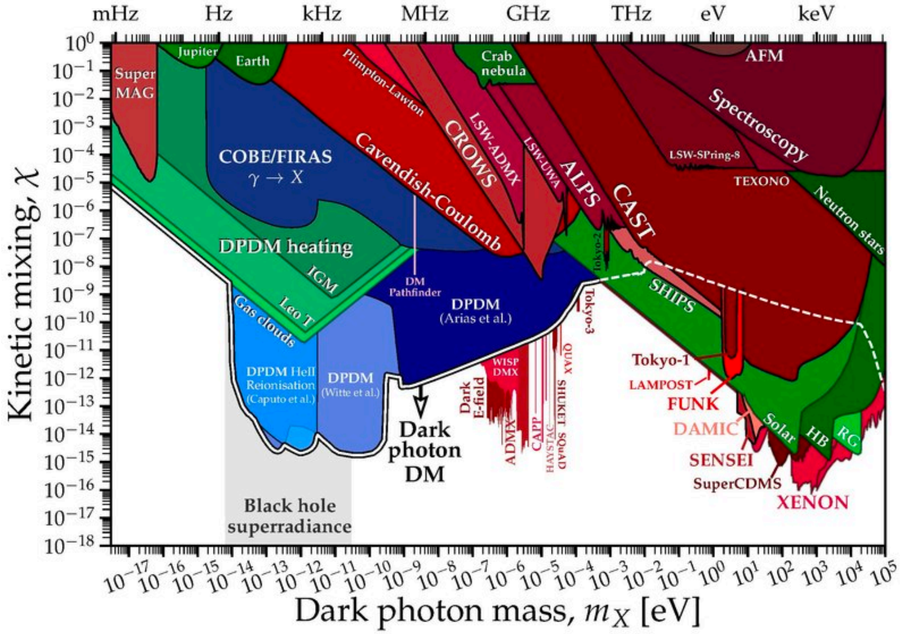
Hualin Mei (University of California, Santa Barbara)

On behalf the MilliQan and MoEDAL-MAPP collaborations

A missing puzzle, the dark matter

- No obvious sign of new physics at the LHC yet
- Dark matter is well motivated from astronomical observations
- Many searches have been carried out for a massive dark photon
- Phenomenology of dark sectors with a massless dark photon is very different





Why millicharged particles

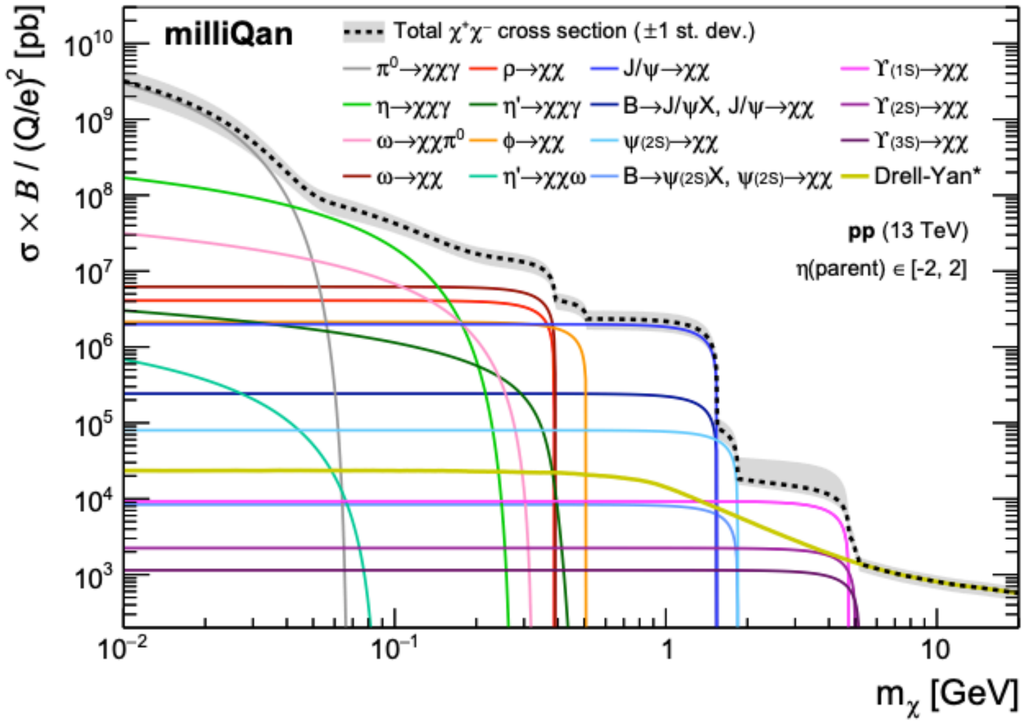
"Dark EM" Mixing of dark photon and SM photon

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

Kinetic Mixing

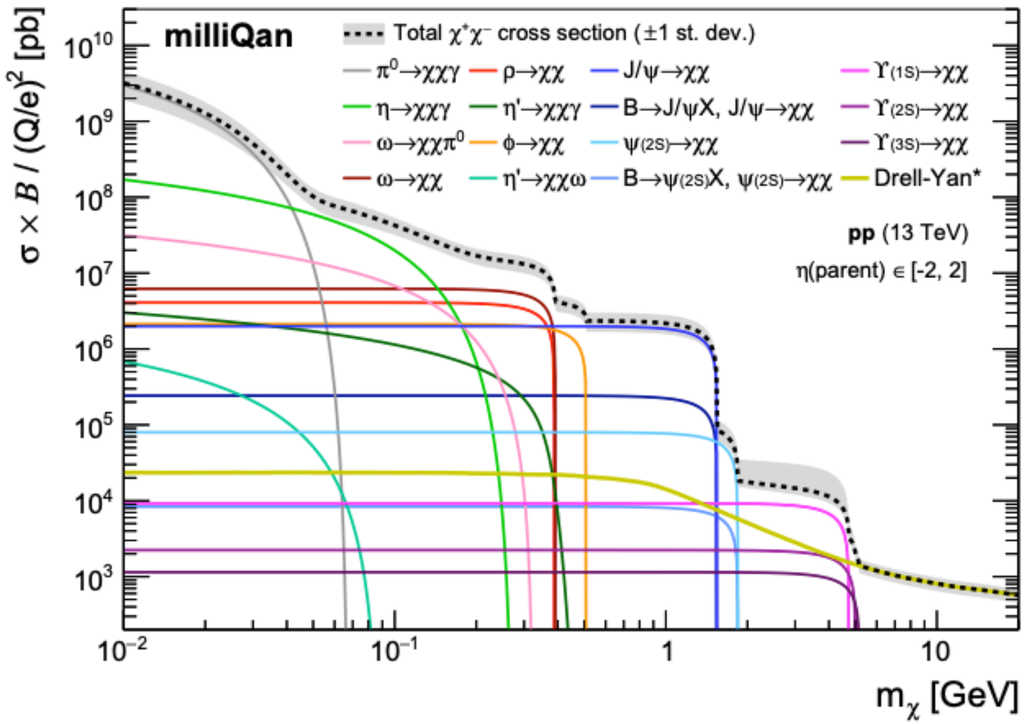
- Consider an dark sector containing a massless U(1) gauge field, B′
- Introduce kinetic mixing κ between B′ and SM hypercharge B ($\kappa \sim \alpha/\pi \sim 10^{-3}$)
- Redefine, $B' \rightarrow B' + \kappa B$, get rid of the mixing term
- After EWSB, $Q_{mCP} = \kappa e' \cos\theta_W$, hence millicharged particle
- These mCPs couple to photons with reduced strength $Q_{mCP}/e \sim 10^{-3}$

Millicharged particles production at LHC



- Any meson decay into e^+e^- through a virtual photon, eg, $J/\Psi \rightarrow e^+e^-$, if kinematically allowed will also decay into mCP-pairs with branching ratio reduced by $(Q_{mCP}/e)^2$
  - Invisible to general purpose detectors at the LHC, need dedicated detectors

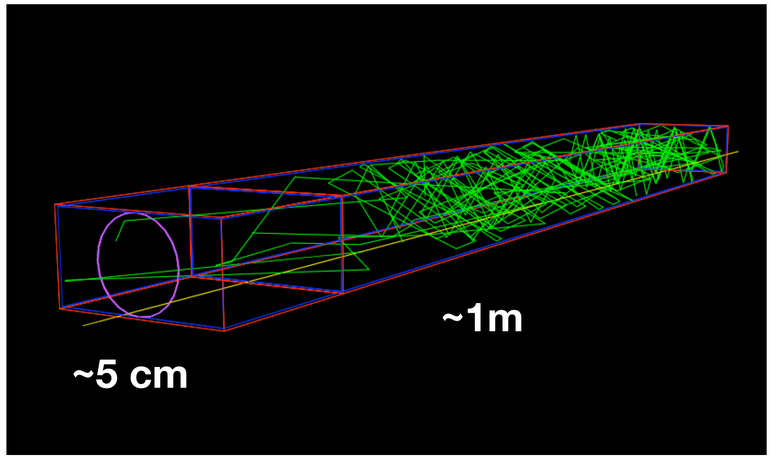
Millicharged particles production at LHC



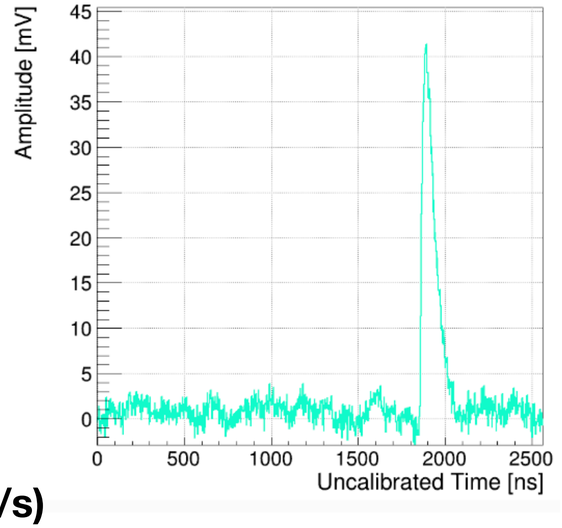
Focus on milliQan and MAPP experiments for today's talk

- Any meson decay into e^+e^- through a virtual photon, eg, $J/\Psi \rightarrow e^+e^-$, if kinematically allowed will also decay into mCP-pairs with branching ratio reduced by $(Q_{mCP}/e)^2$
  - Invisible to general purpose detectors at the LHC, need dedicated detectors

MilliQan detector principle



Bar = Scintillator + PMT arrays

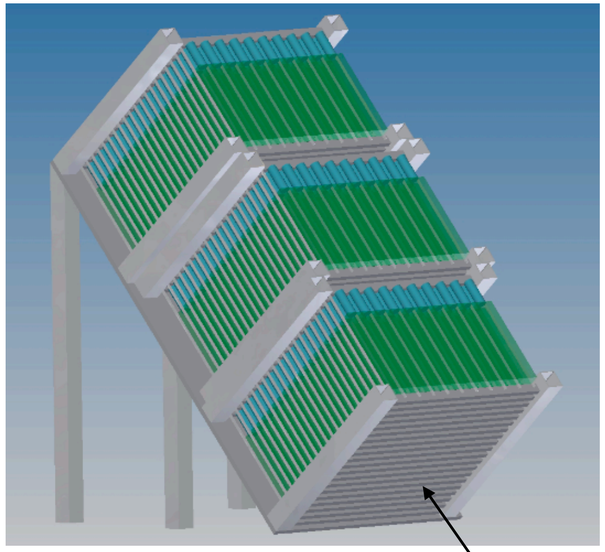


O(GHz/s)

Initial design in 2016 letter of intent:

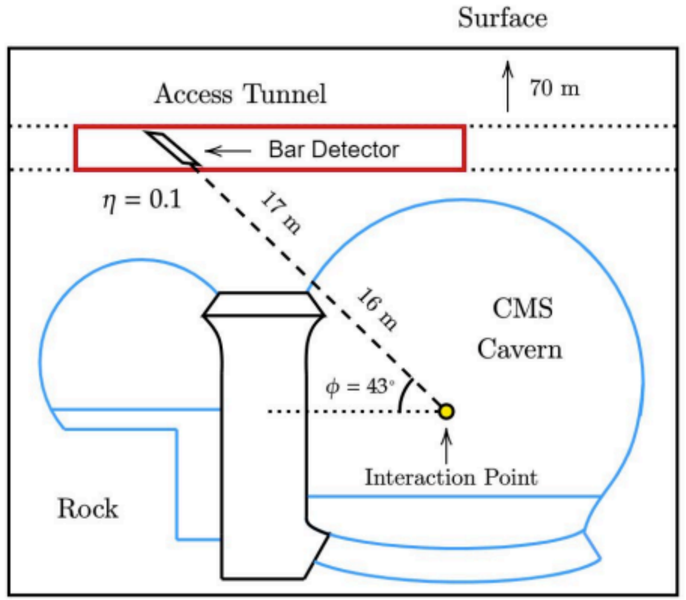
1200 scintillating bars in 3 layers

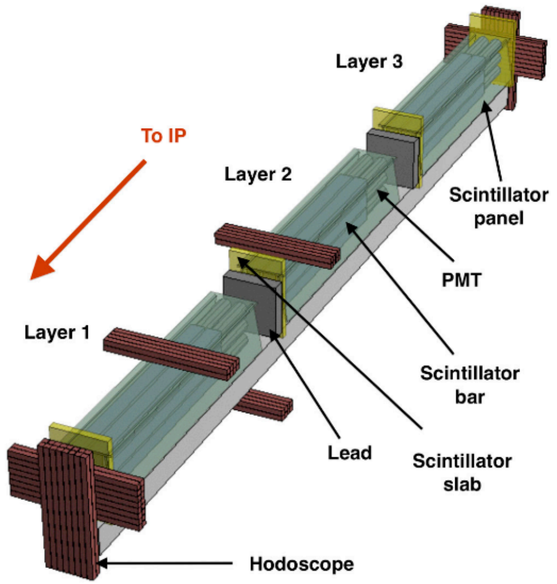
$20 \times 20 \times 3$

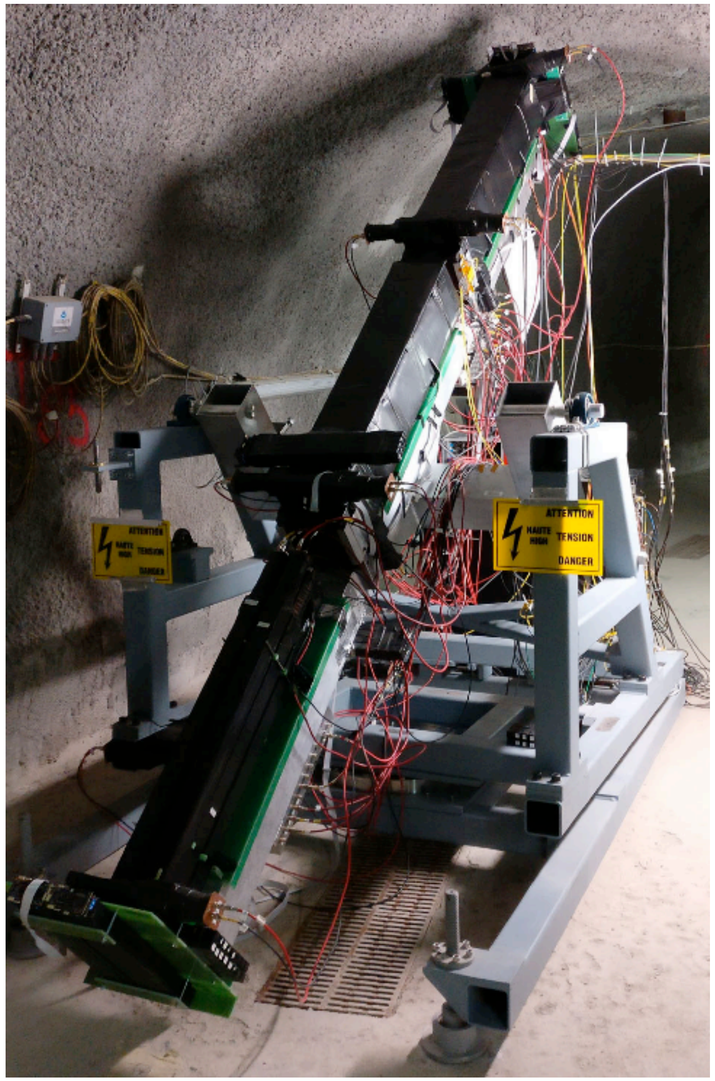


- Search for milli-charged particles produced at the LHC collisions
- Multi-layer of ~1m long scintillator bars + PMT arrays
- Sensitive to milli-charged particles, expect few photo-electrons (PEs) for particles with $O(10^{-3})$ charge
- Use high sampling frequency electronics to capture PE signals

MilliQan demonstrator

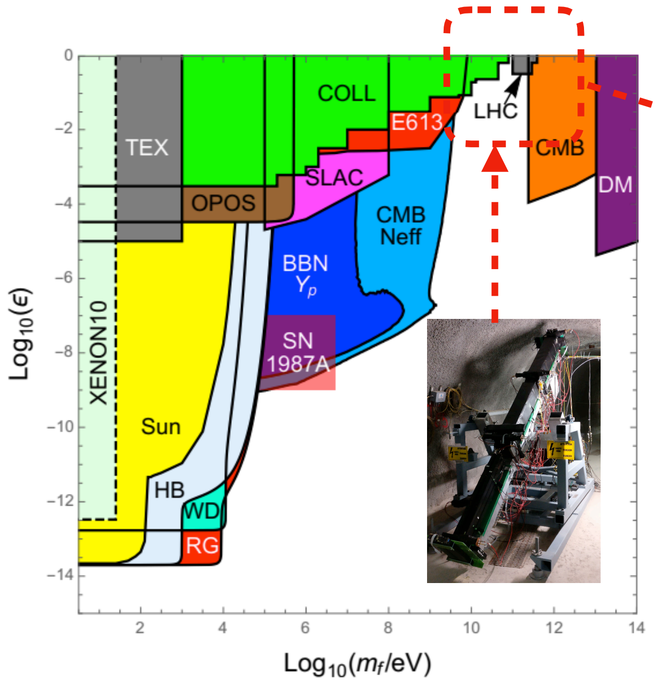


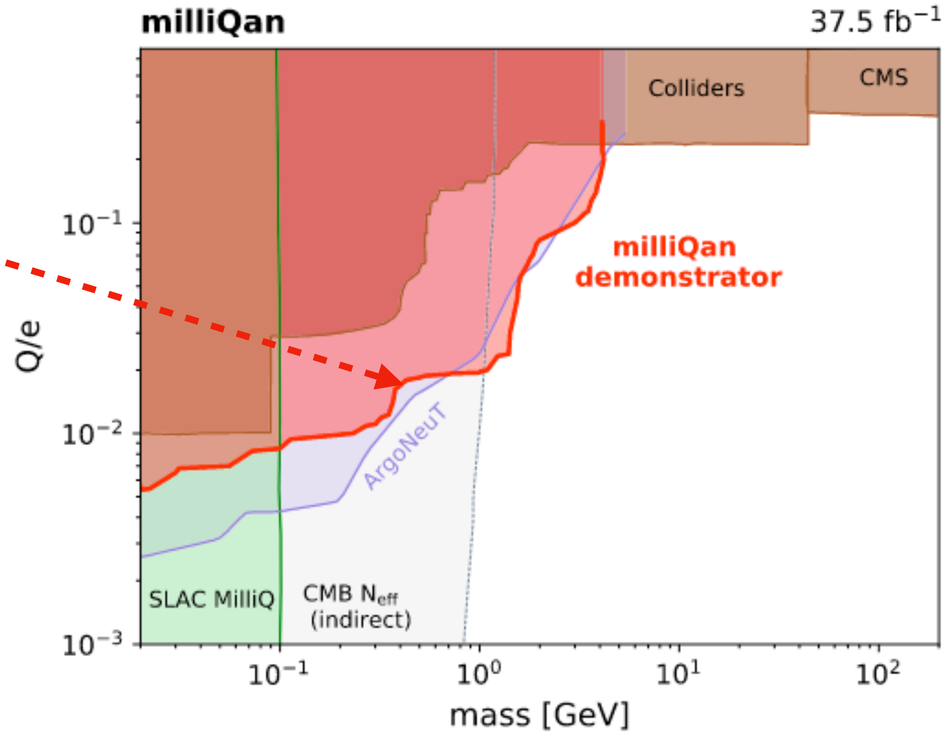




- In 2017, demonstrator was deployed at CMS site, 3 layers of 2×3 bars
- Other components (panel, hodoscope) to characterize/reduce certain background processes (through-going muon, neutrons etc)
- ~31m from CMS IP, ~17m of rock shielding

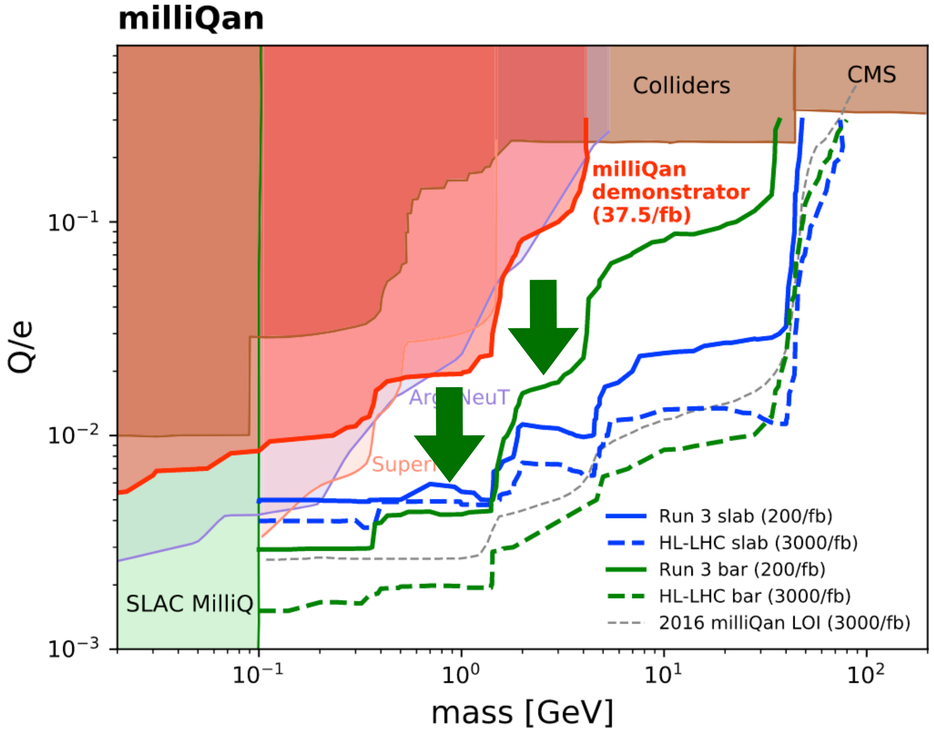
MilliQan demonstrator

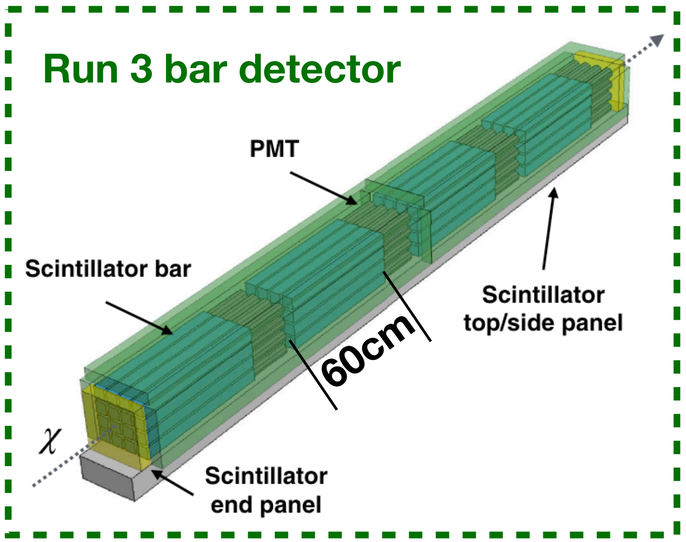


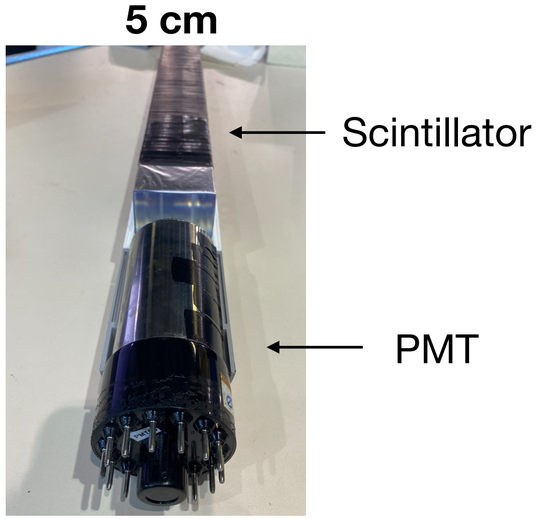


- Previous LHC experiments are not designed for searching for milli-charged particles
- MilliQan demonstrator, amount to ~1% of actual detector, can provide complementary sensitivity to milli-charged particles at the LHC
  - With ~2000 hours of data in 2018 during the LHC Run 2

MilliQan Run 3 detectors





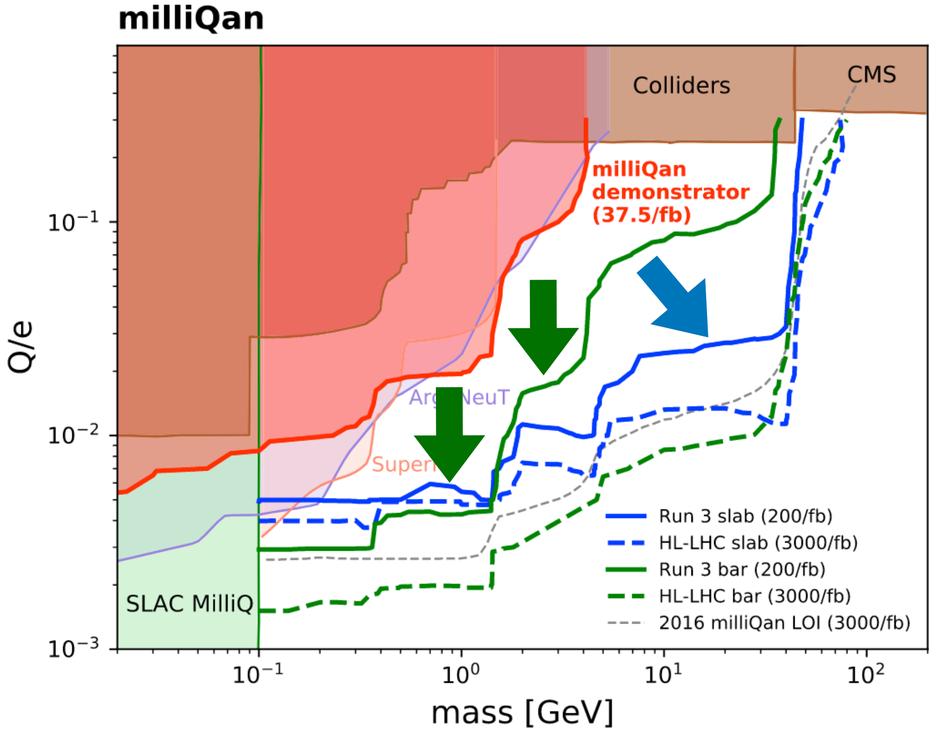


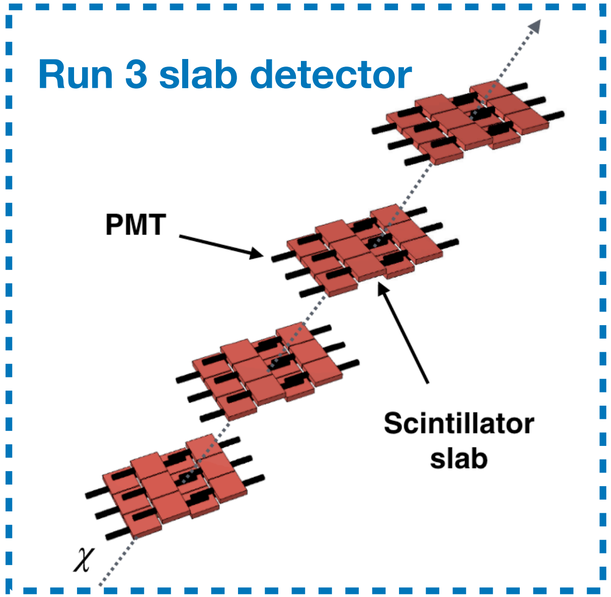
Two new detectors are under construction and commissioning!

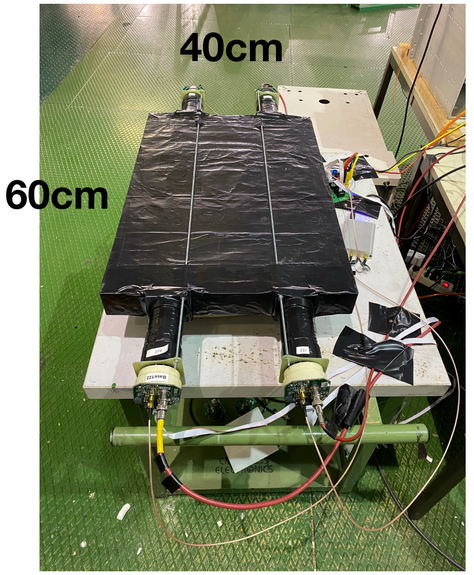
arXiv:2104.07151

- 4 layers of bars, better background rejection
- Bar design similar to demonstrator
- Each layer has 4×4 bars, 2.5 higher sensitive area
- Improve PMT signal amplification, better SPE reconstruction efficiency
- LED system for calibration and monitoring

MilliQan Run 3 detectors







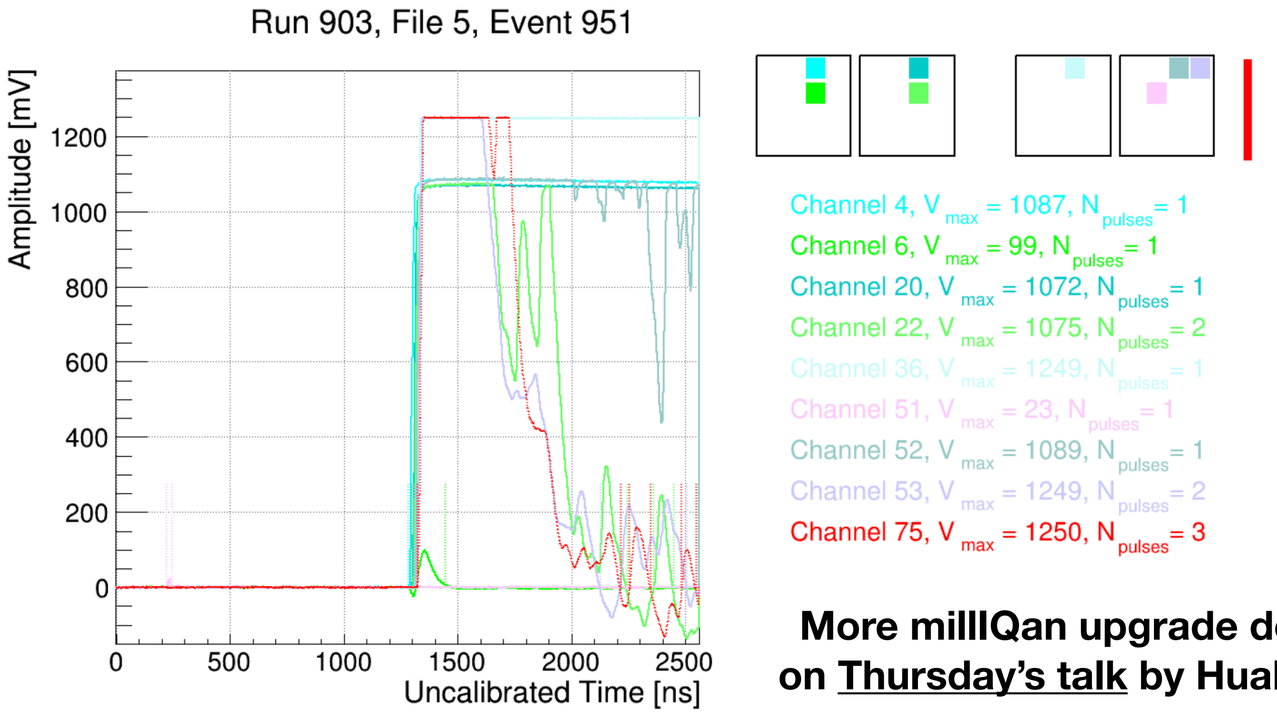
Two new detectors are under construction and commissioning!

arXiv:2104.07151

- 4 layers of slabs, thinner scintillator with larger active area
- Improve sensitivity for milli-charged particle with large mass (>~1GeV)
- Each layer has 3×4 slabs
- Each slab has 4 PMTs attached to increase light collection efficiency
- Same PMT amplification and LED calibration system as bar detector

Current status of the bar detector

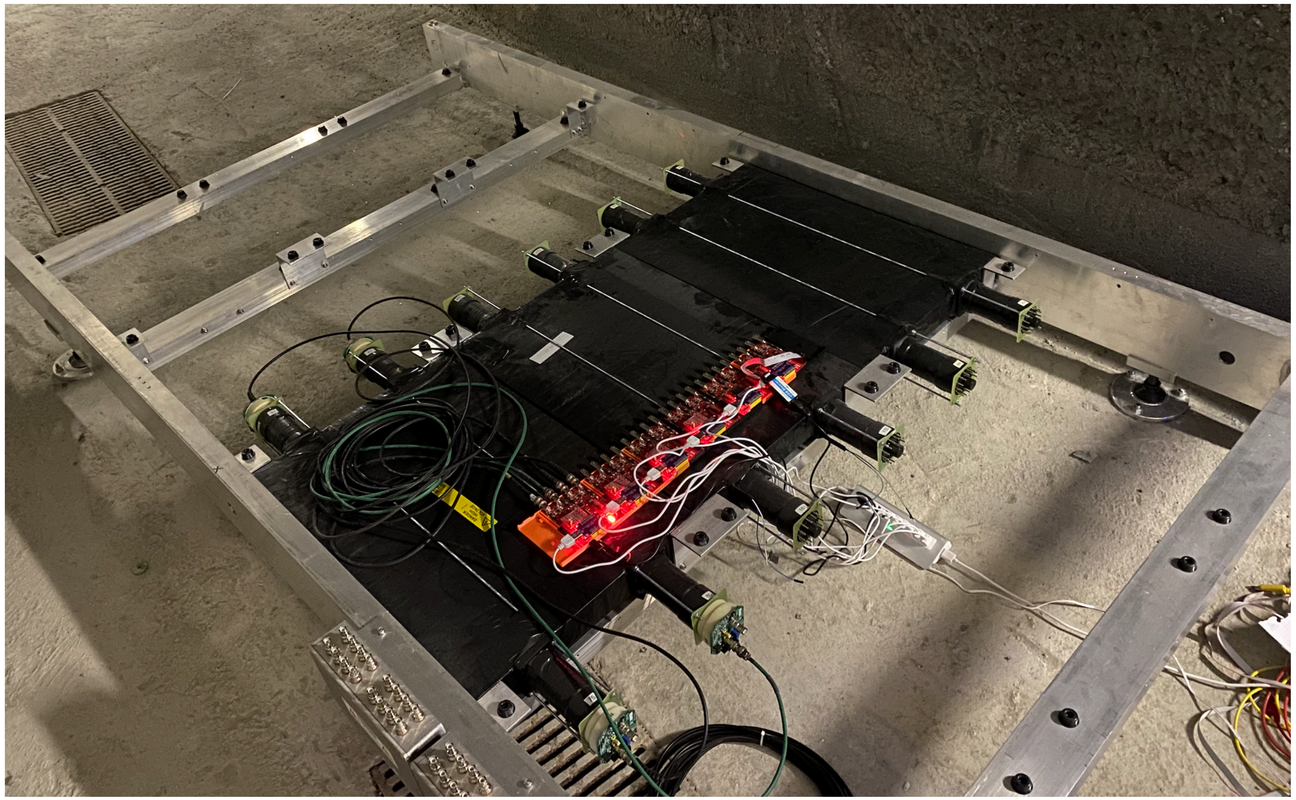
A muon candidate



More milliQan upgrade details on Thursday's talk by Hualin Mei

- The full bar detector has been installed in the final position
- Actively taking data to commission and calibrate the detector, expect physics data taking in coming weeks

Current status of the slab detector

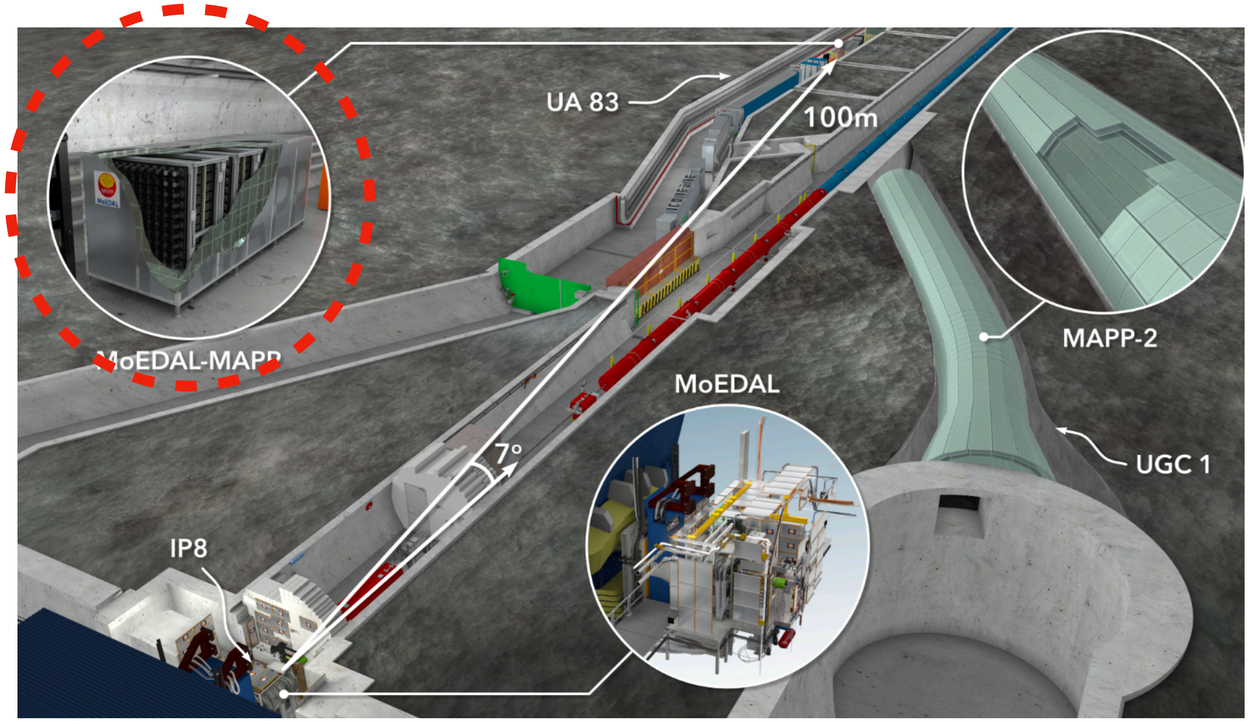


More milllQan upgrade details on Thursday's talk by Hualin Mei

Slabs ready for installation

- First layer of the slab detector and its DAQ system is being installed
- Full slab detector will be installed and commissioned in the coming 1-2 months

MoEDAL Apparatus for Penetrating Particles (MAPP)



LHCb IP

Installation on going

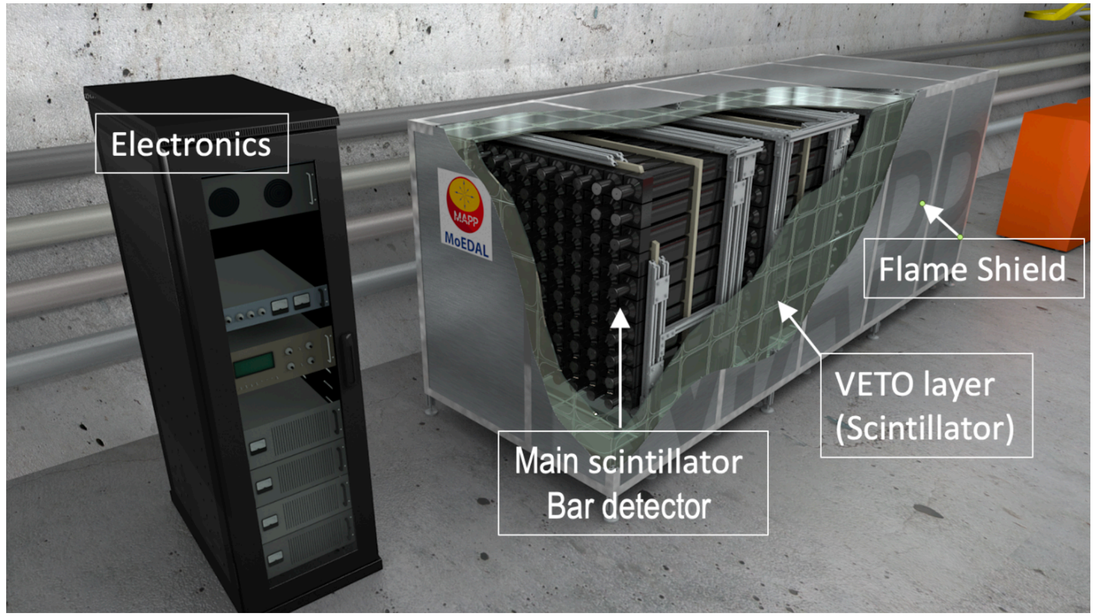
- A sub-detector added to the baseline MoEDAL detector

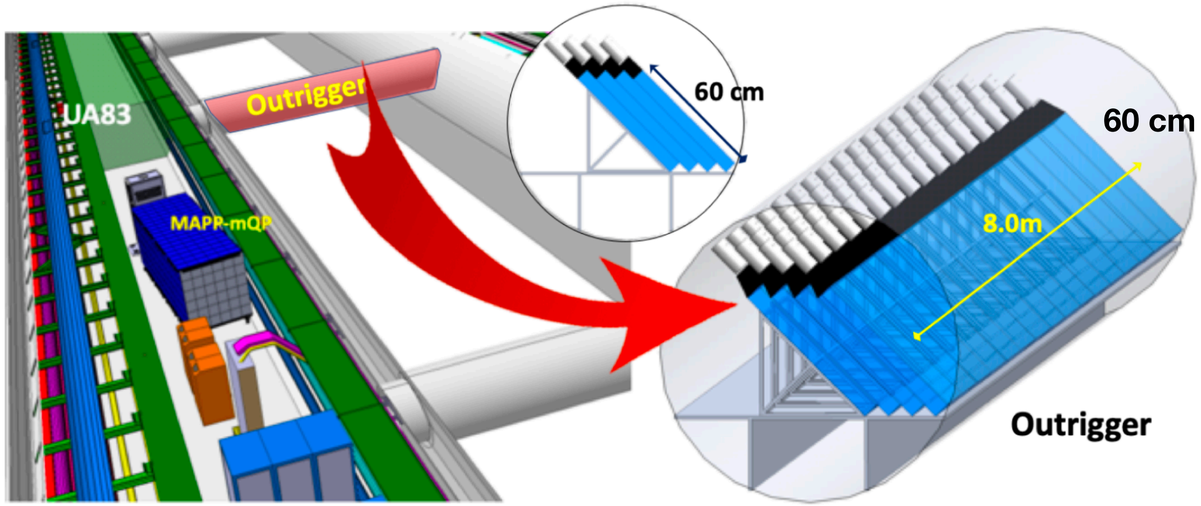
- Part of Run-3 Phase-1 upgrade program, extending expands the physics reach of MoEDAL to millicharge particles and LLPs

LLP search at MoEDAL-MAPP
See tomorrow's talk by Vasiliki Mitsou

arxiv 2209.03988

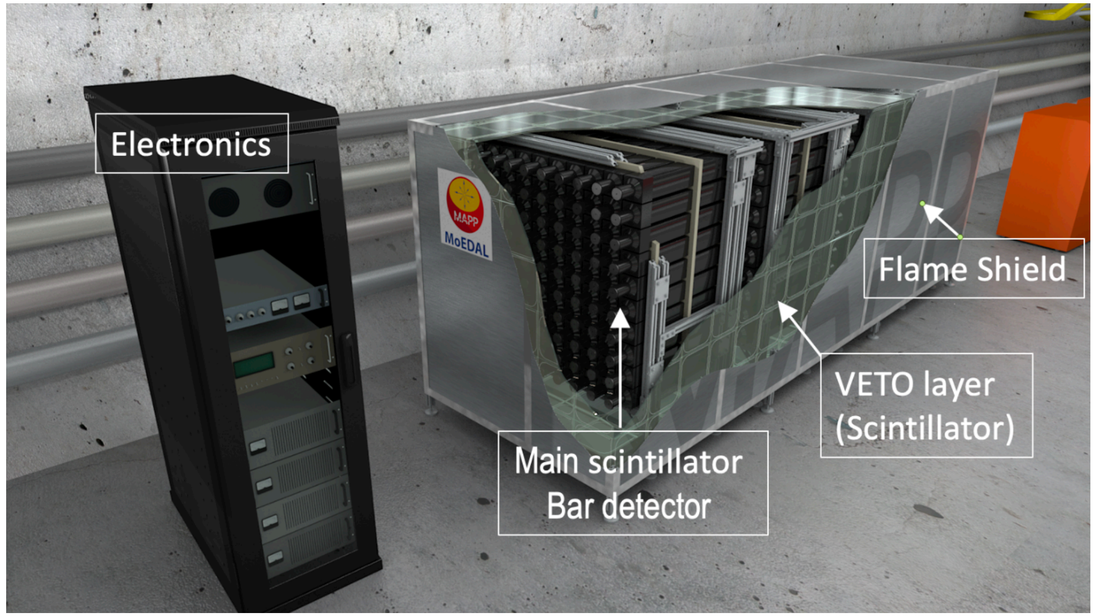
Bar detector and Outrigger of MAPP

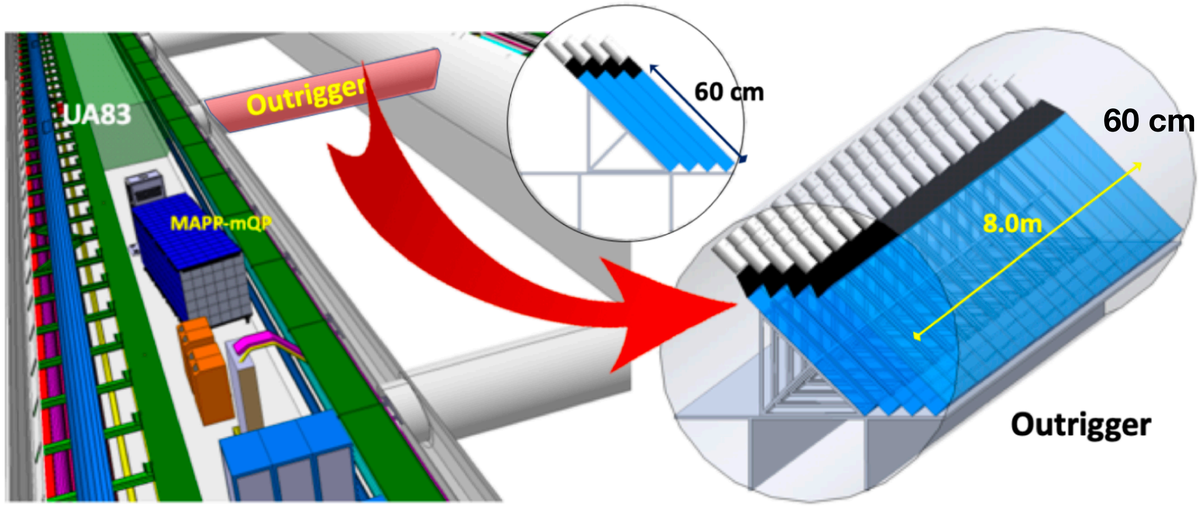


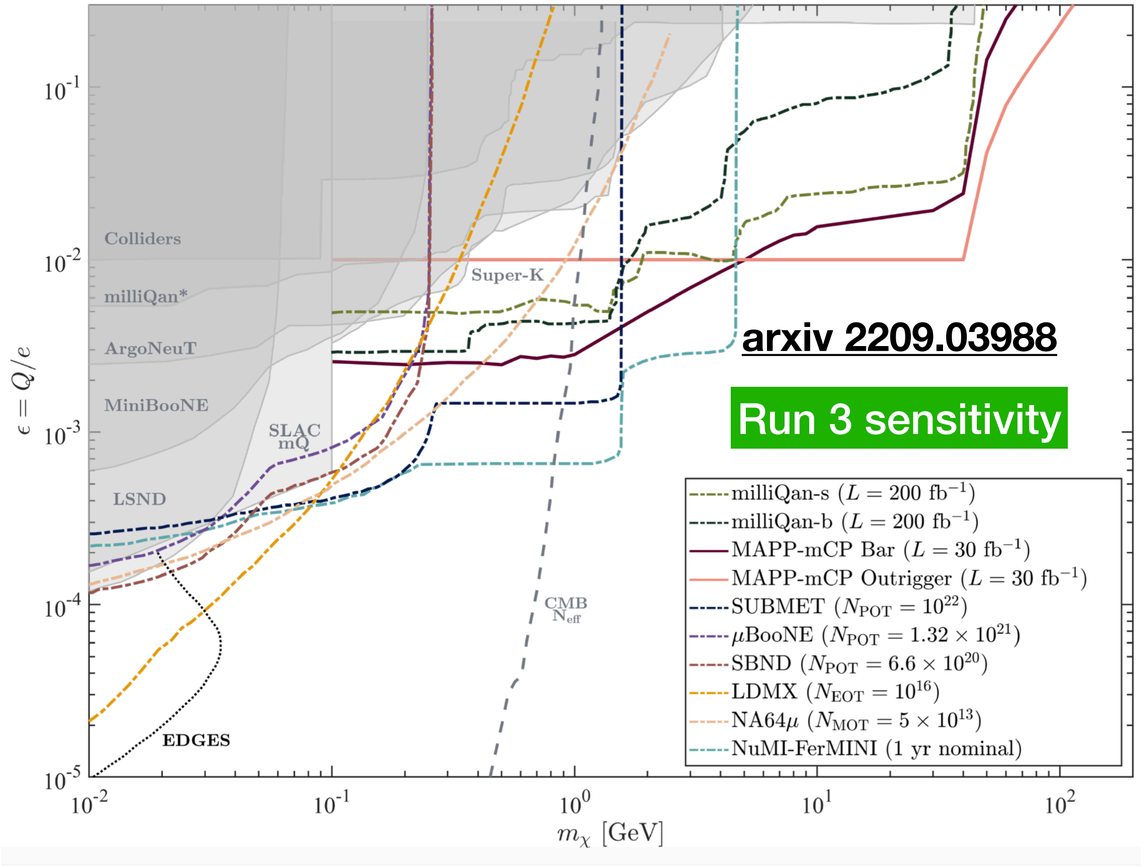


- Bar detector
  - 4 layers of 10 ×10 scintillator+PMT array
  - Scintillator: 10 cm × 10 cm × 75 cm
  - Enclosed by scintillator veto layer
- Outrigger
  - 2-6 degree of beam axis
  - 4 layers of scintillator planks, each layer contains 16 50 cm × 60 cm scintillator plate
    - Each plate readout by 1 PMT

Bar detector and Outrigger of MAPP







- Promising sensitivity at upcoming operations

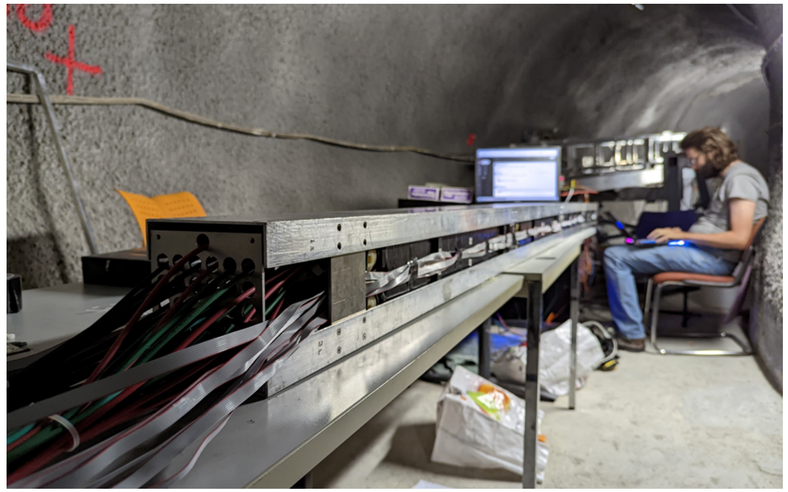
Summary

- Dedicated detectors required to probe BSM phase space that is inaccessible by general detectors at the LHC
- MilliQan and MAPP experiments are under preparation to look for millicharged particles using future LHC operations
- Both experiments have 2 types of design of the detector, bar and slab (outrigger) detector to complement sensitivity in Q~m plan
- On-track for Run 3 physics data taking starting from 2023

Backup

MilliQan run 3 bar detector construction

4 bars assembled into an unit, all bars are made light-tight with black taps



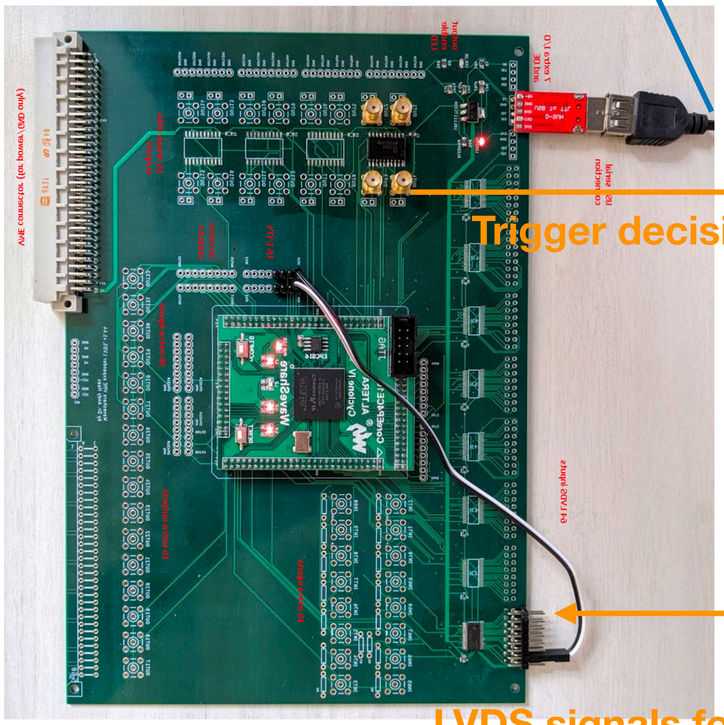
4 units (= 16 bars) assembled into a supermodule, HV/LV/signal cables are attached to customized PMT readout unit

4 supermodules (= 64 bars) put into the cage to make the final bar detector

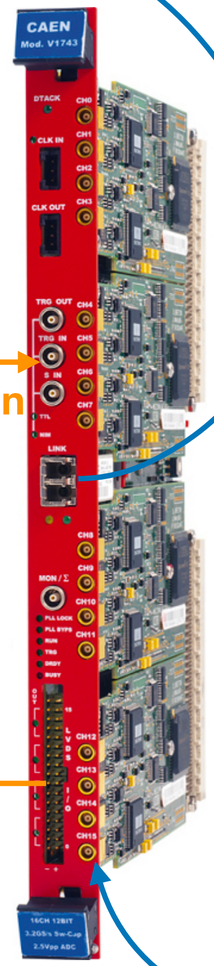
MilliQan Run 3 DAQ system

Trigger information

Digitized pulses

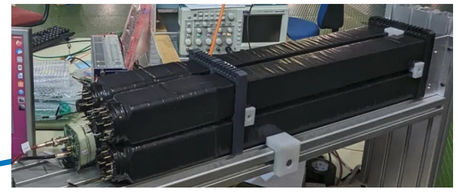


Trigger decision



LVDS signals for trigger decision

Amplified PMT pulse



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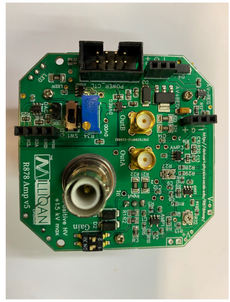

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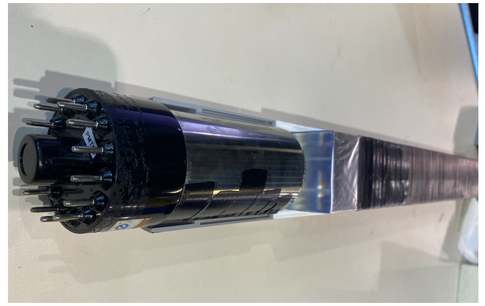
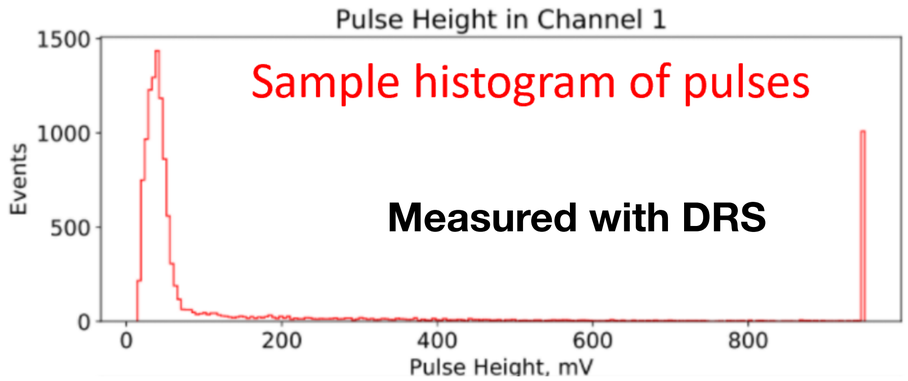
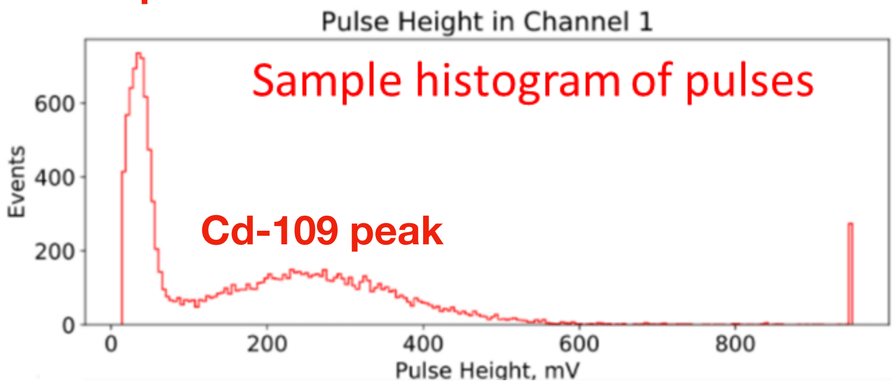


- PMT output amplified with customized base, O(100) ns long output pulse shape => **high SPE efficiency**
- CAEN V1743 digitizer to sample PMT pulses, 16 channel, O(GHz) sampling frequency, O(1000) ns readout window **=> reconstruct complete pulse information**
- Customized trigger board equipped with Altera Cyclone IV FPGA for trigger decision making => **max flexibility**

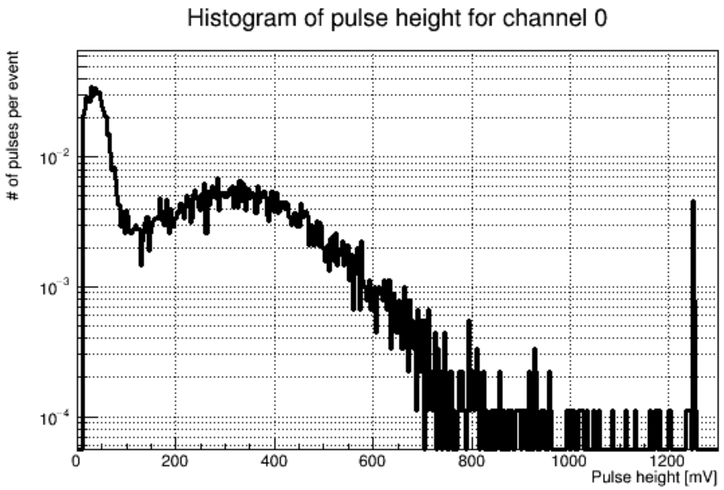
Various calibration activities for milliQan



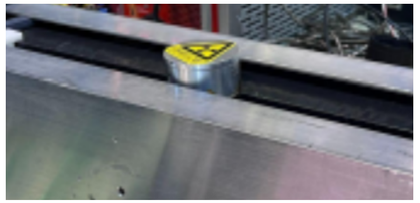
SPE peak



Measured with DAQ



Calibration with Cd-109

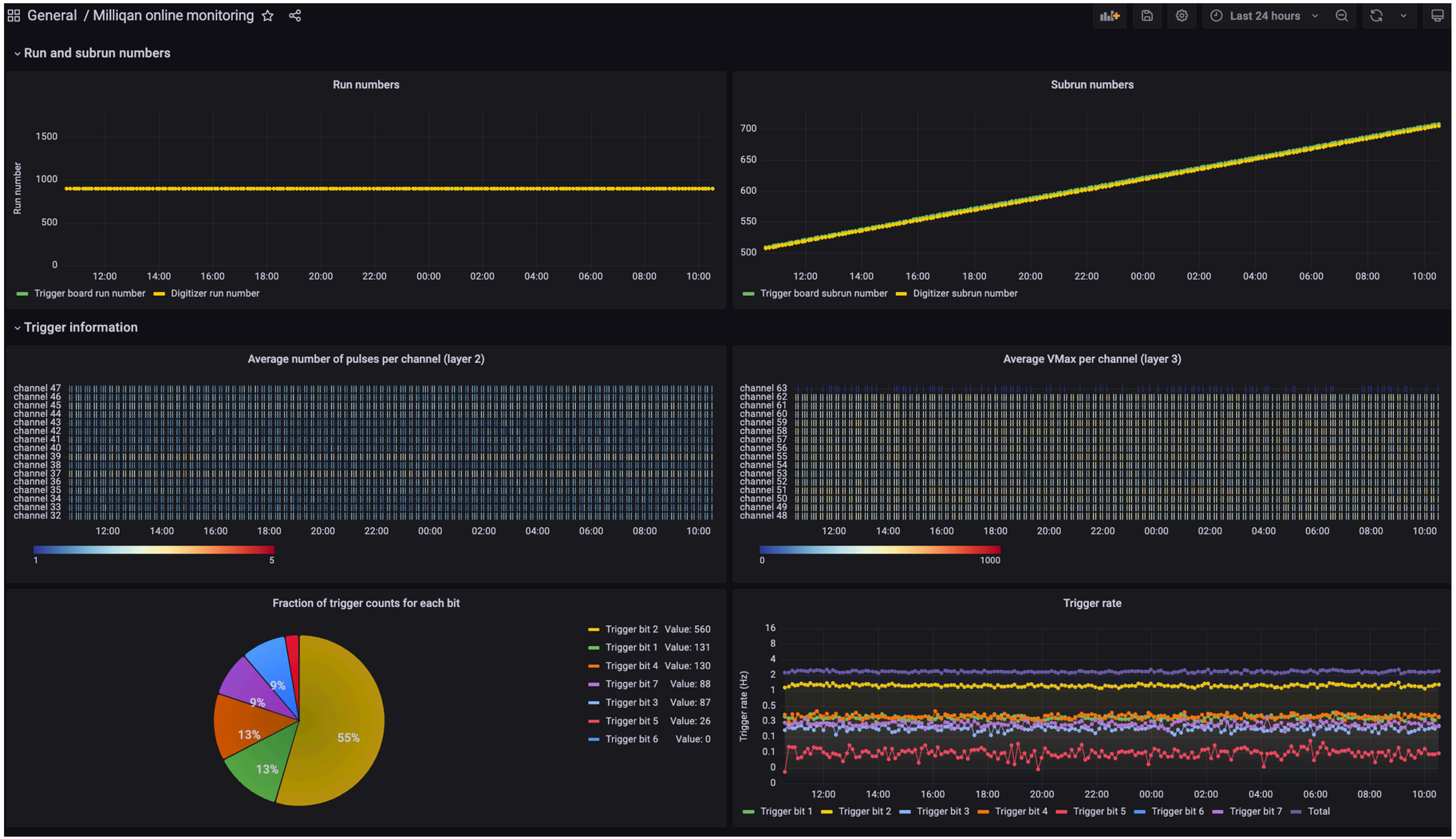


3.1.1 X Radiations

		Energy (keV)	Relative probability
X_K			
	$K\alpha_2$	21,9906	53,05
	$K\alpha_1$	22,16317	100
	$K\beta_3$	24,9118	27,7
	$K\beta_1$	24,9427	
	$K\beta''_5$	25,146	
	$K\beta_2$	25,4567	4,82
	$K\beta_4$	25,512	

- Before/after installation, each PMT's response to SPE and radioactive source are measured using digital oscilloscope and actual DAQ chain of the experiment => a measure of NPE/keV (energy response)
- Use through-going muon (cosmic or from CMS IP) for timing calibration

MilliQan Online monitoring



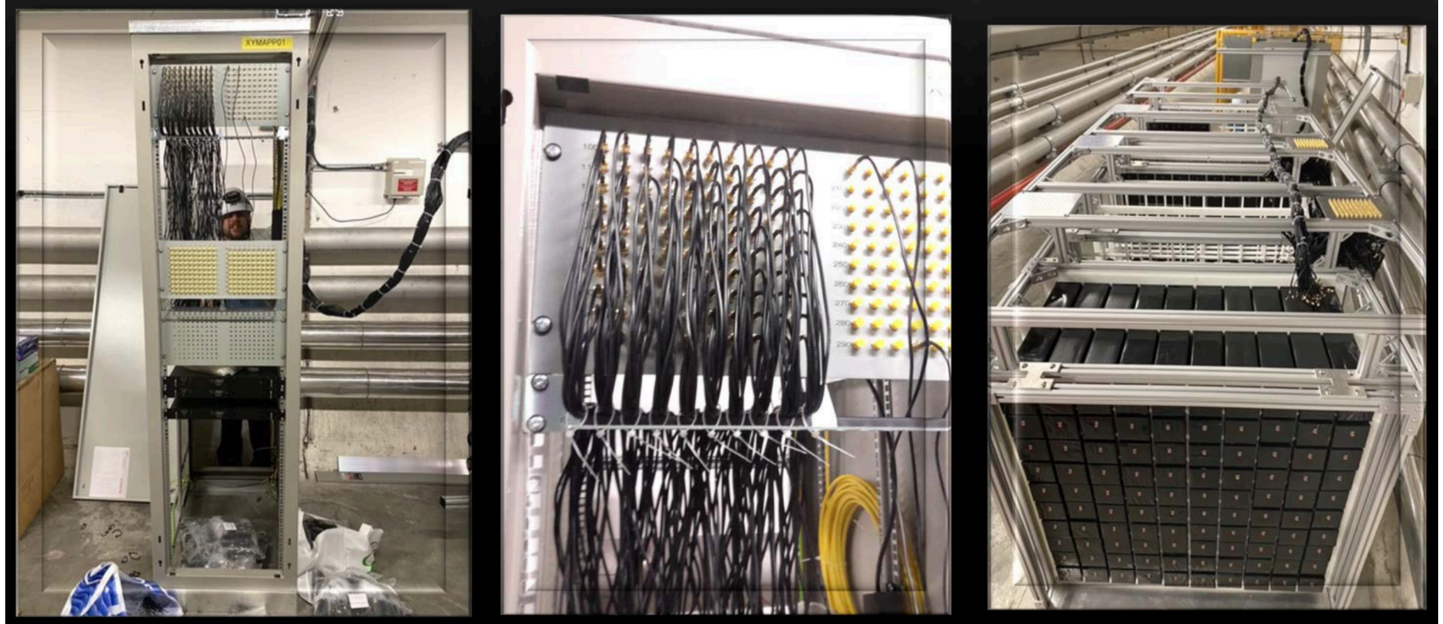
- Web based monitoring and run control tools have been developed to facilitate smooth operation

PMT pulse properties

Trigger rate profile

MAPP-1 installation status

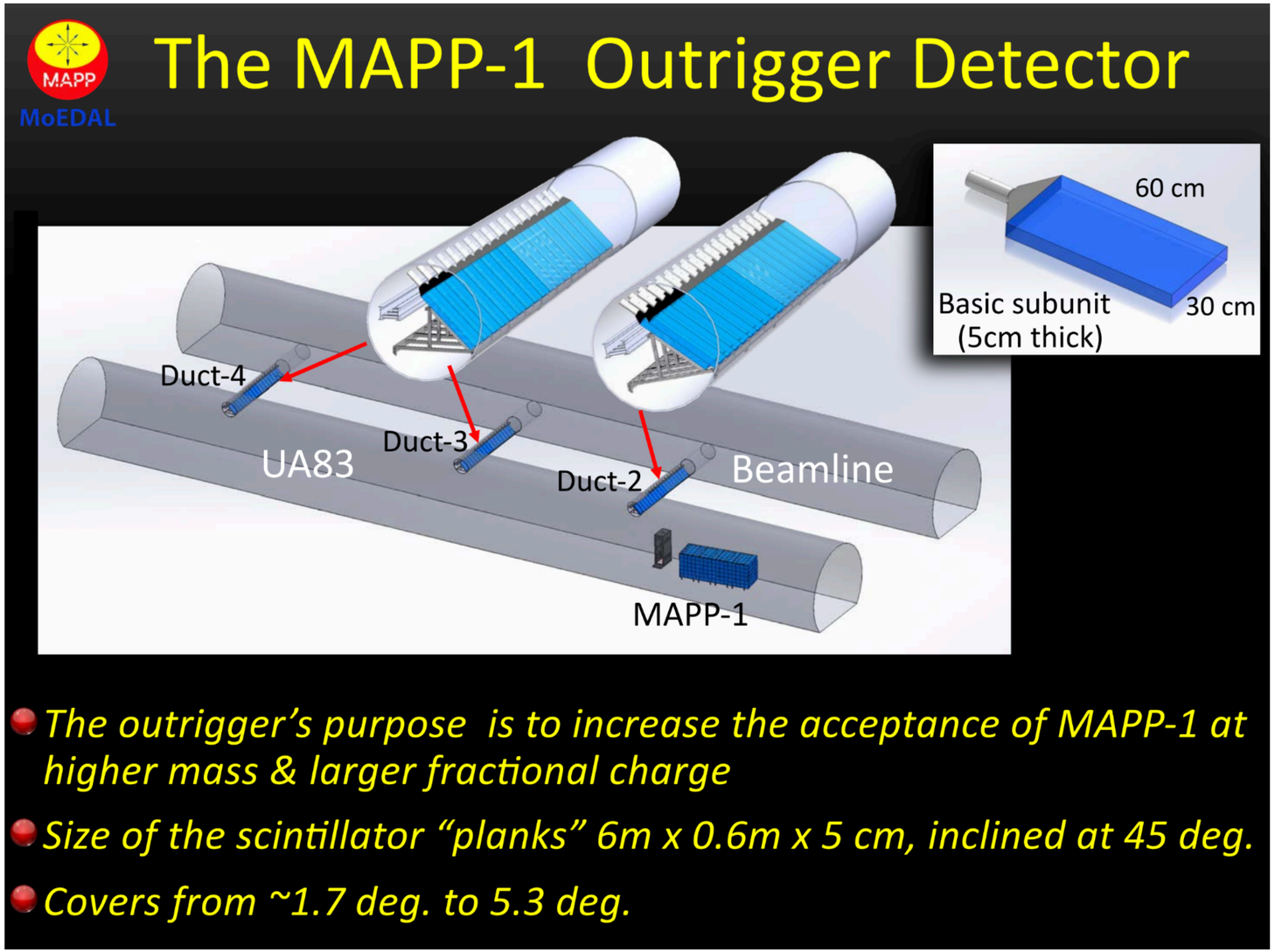
MAPP-1 is Currently Being Installed



- *Installation proceeds when access to UA83 is permitted, the above photographs were taken in March 2023*
- *The next installation period will be in the TS in June 2023*
- *We expect to start taking data in July 2023.*

Slides taken from here at Corfu 2023

MAPP-1 Outrigger detector



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