Search for millicharged particles with scintillation based detectors at the LHC

Snowmass EF09 meeting
17th of September 2021

Francesco Setti on behalf of the milliQan collaboration

This speaker was supported by the DOE Office of Science

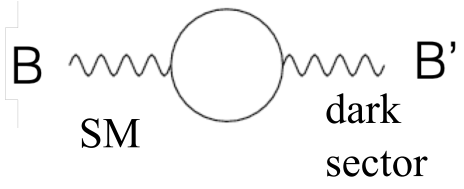
Why Millicharged Particles?

- Introduce new massless $U'(1)$ dark boson B' & kinetic mixing with SM $U(1)$ hypercharge – **link to dark sector**

kinetic mixing term

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

massless $U'(1)$ dark boson



$\kappa \sim 10^{-2} - 10^{-3}$
(EM strength $\sim \alpha/\pi$)

- Add fermion charged under new $U'(1)$

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

- Redefine gauge field $B' \rightarrow B' - \kappa B$: removes mixing term & generates hypercharge for new fermion

$$\mathscr{L} = \mathscr{L}_{SM} - \frac{1}{4} B'_{\mu\nu} B'^{\mu\nu} + i\bar{\psi}(\partial + i\kappa e'B + ie'B' + iM_{mCP})\psi$$

new fermion has small EM charge
(**milli-charged particle or mCP**)

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Searches for Millicharged Particles

- **Millicharged Particles (mCPs) can be the link to the dark sector!**

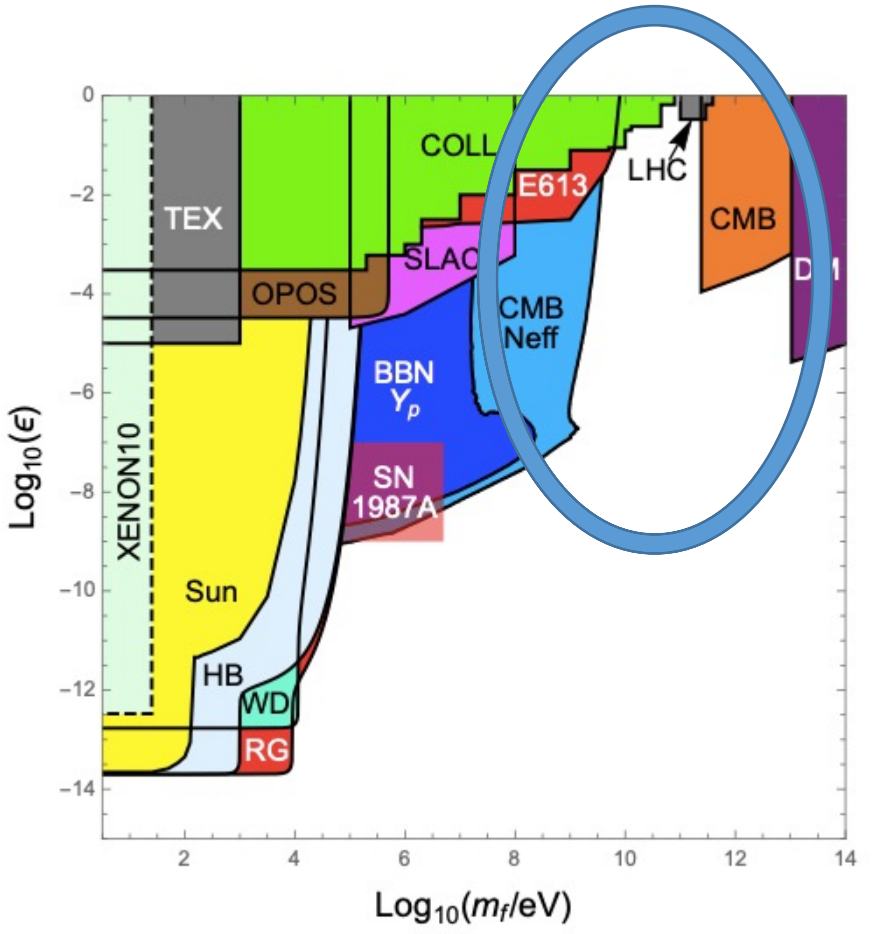
- mCP production rate at LHC well understood
  - processes with $\gamma e^+ e^-$ vertex also produce mCP pairs, if kinematically allowed, suppressed by $(Q/e)^2$
  - $Z \rightarrow$mCP mCP allowed, after assumptions on weak hypercharge
  - **cross-section only depends on mCP mass & charge!**

- Broad set of efforts to constrain mCP phase space:
  - Solar effects
  - Cosmological bounds
  - Stars and supernovae
  - Colliders (LHC)
  - Beam dumps (SLAC)

  indirect searches

- LHC has unique reach in unexplored high mass region (~GeV)
  - general purpose detectors are blind to mCPs

- Target this high mass region with milliQan!



Current status of constraints on fermionic mCPs in the mass (m_f) and charge $(Q = \epsilon e)$ phase space. arXiv:1511.01122

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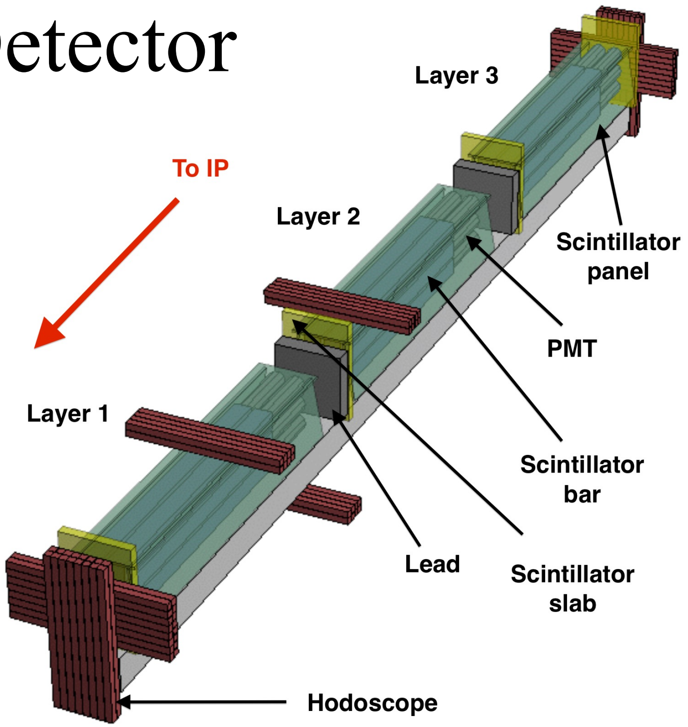
milliQan – A Scintillation Based Detector

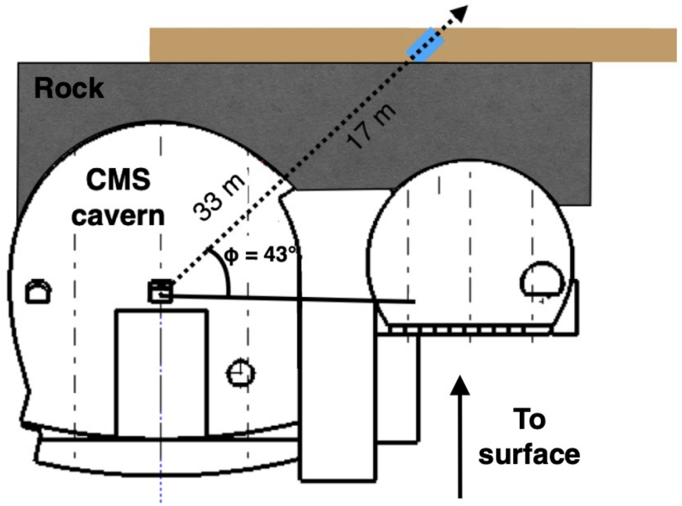
- Scintillator bars + PMTs allow small ionisation signal from mCPs to be detected:
  - ionisation $\propto \epsilon^2 \rightarrow$ long bars boost sensitivity to charges as low as $0.001e$



- We built a small (32 channels) demonstrator of full milliQan detector:
  → understand main sources of background
  → study detector response and performance

- 70m underground and 33m from CMS IP (17m of rock) → **shield from beam particles**
  - same location as proposed for full milliQan detector

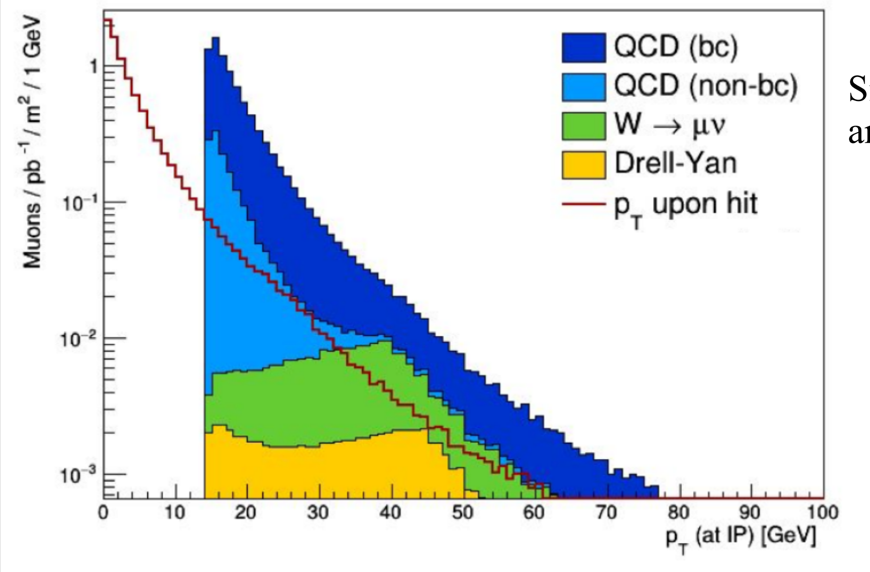
- Multiple layers to reject background by requiring:
  - timing coincidence between all hits (∼15ns)
  - paths pointing towards the IP



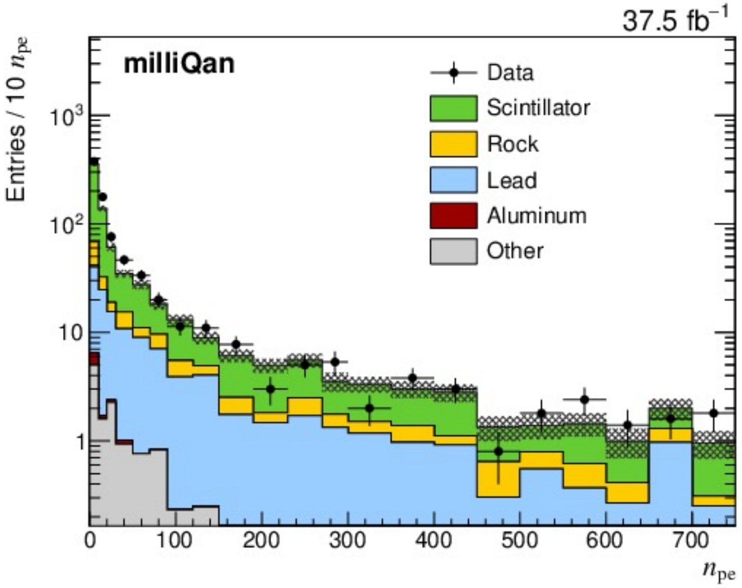
The prototype location is at 43° from the horizontal in the azimuthal plane and at η =0.1 from the IP.

milliQan Operation

- milliQan collected ~**37fb^{-1}** of data in 2018 (2100h)
- Operation experience in: triggering and data acquisition
- Feasibility studies for the full detector: alignment, channel calibrations, background measurements
- The measured muon rate of 0.20/pb^{-1} is in good agreement with the predicted value 0.25 $\pm$ 0.08/pb^{-1}.
- Full GEANT 4 simulation, validated with data



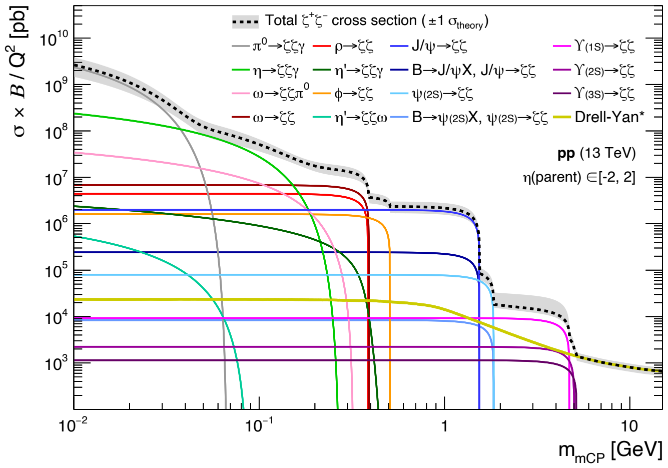
Simulated muon p_T and muon rate.



nPE distribution of shower particles from beam muons in the detector.

milliQan Results

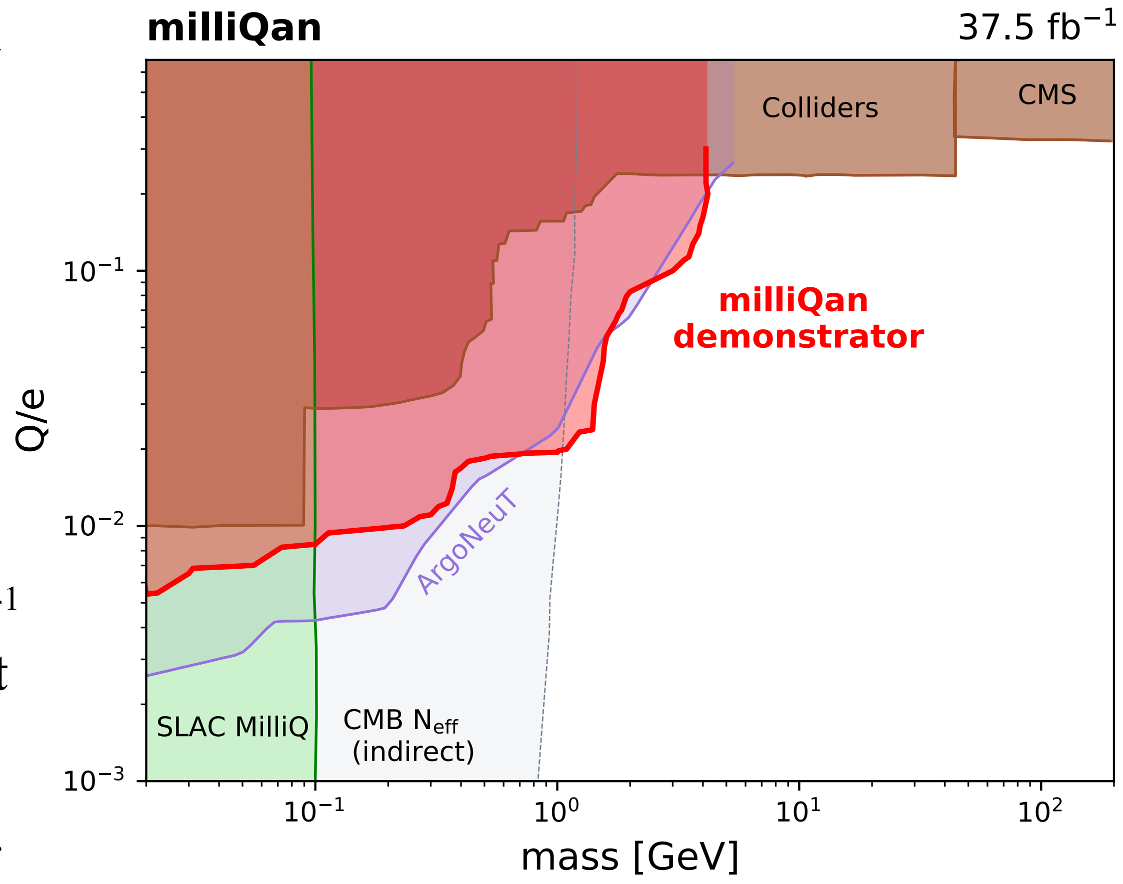
- mCPs generated over broad spectrum of production modes & signal efficiency evaluated with GEANT4 detector simulation



- Despite being ~1% of total detector and collecting only 37fb^{-1} of data, demonstrator set competitive and **model independent constraints** on mCPs phase space

- The demonstrator also provided quantitative understanding of backgrounds and detector performance

- **Use this knowledge to guide designs for Run 3 and beyond!**



Demonstrator results published in PhysRevD.102.032002.

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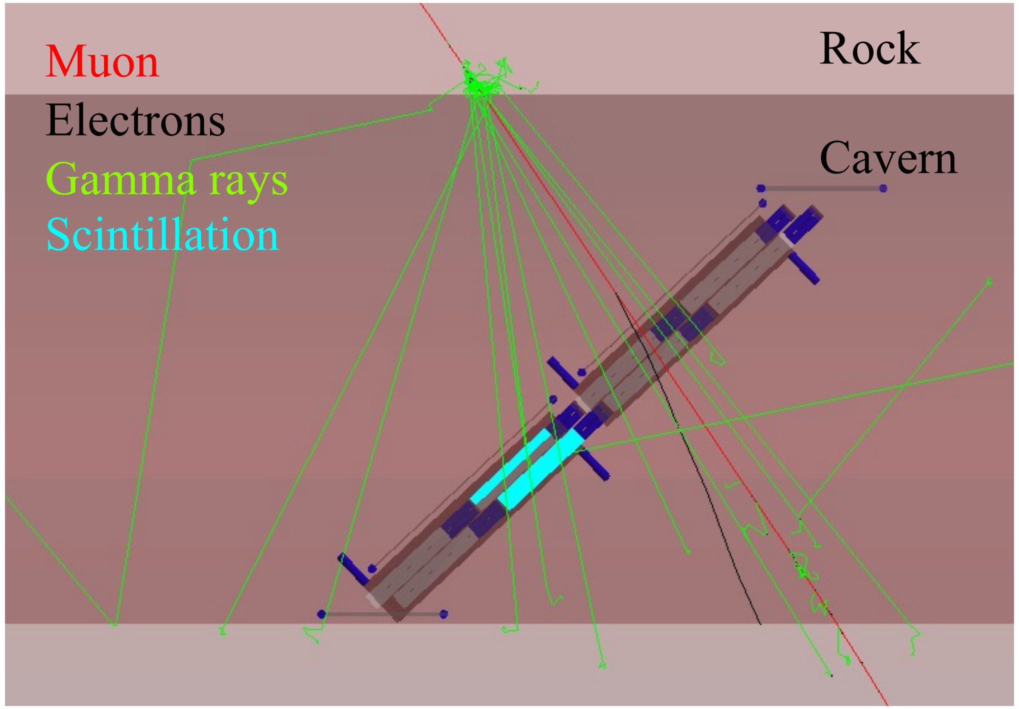
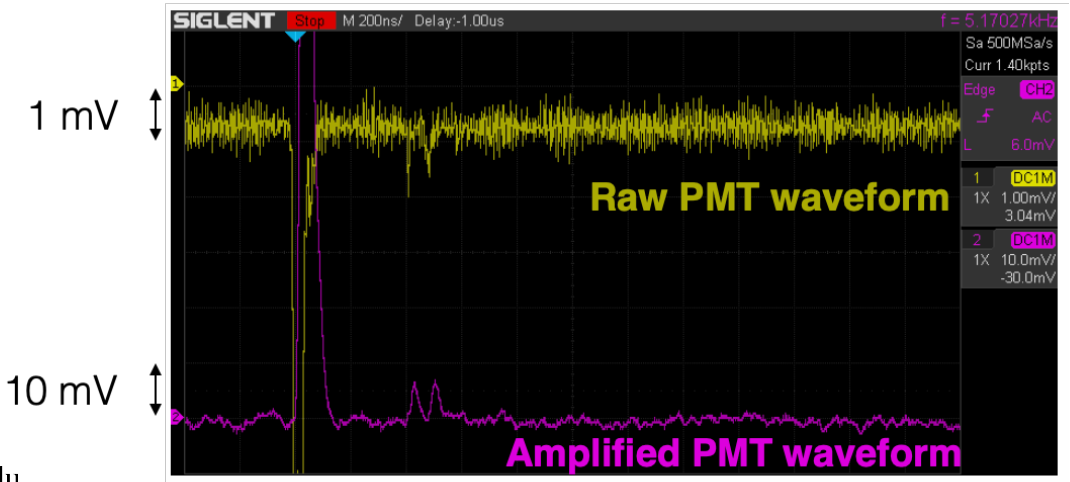
Run 3 milliQan Upgrades

- Designed upgraded milliQan detector using lessons learned from the demonstrator
    - Additional fourth layer needed to suppress cosmic showers (main background)
    - Increased thickness to 5cm of scintillator panels/slabs to veto cosmic showers
    - Dedicated signal amplification electronics to improve detection of low energy deposits
    - Standalone slab detector to target specific phase space region of mCPs

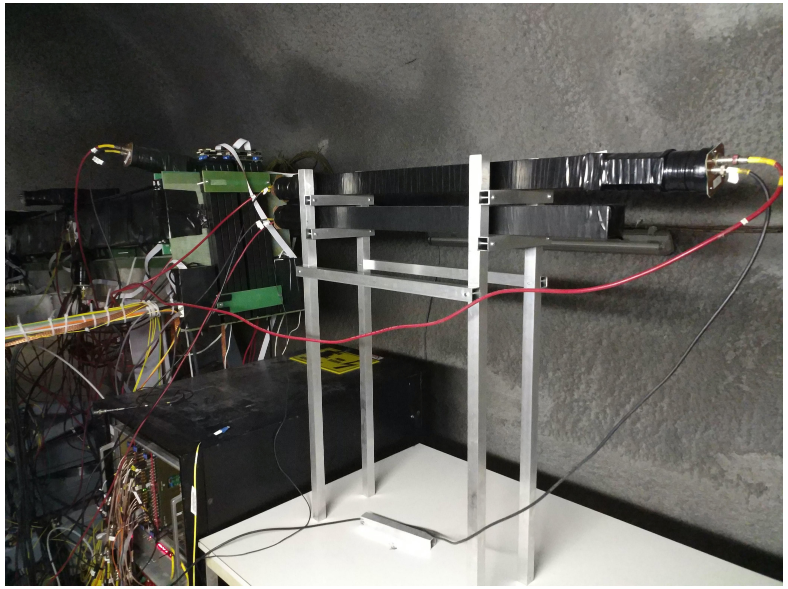
- **Secured funding for upgraded milliQan layout for Run 3!**

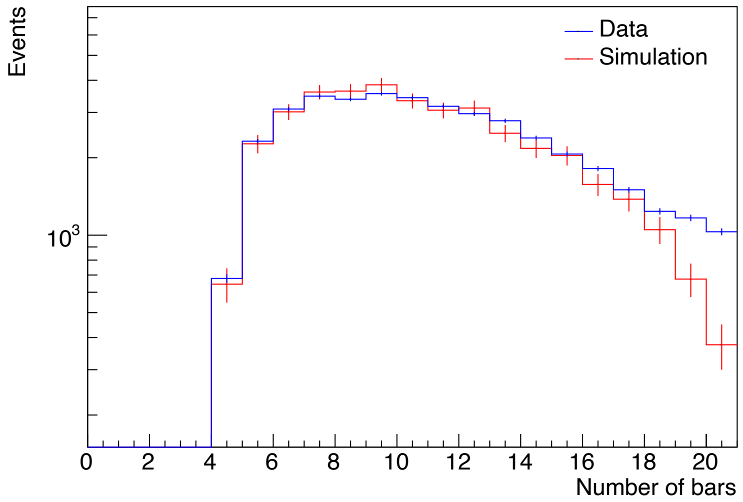




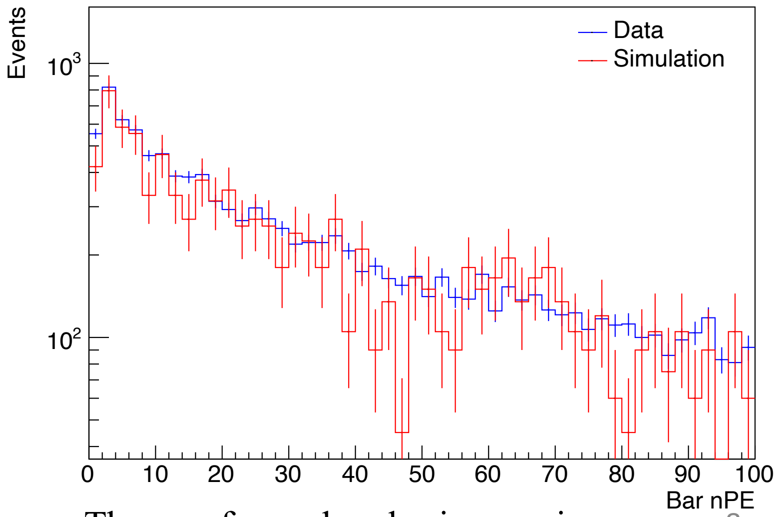
Cosmic Background Characterisation

- Cosmic muons propagated from the surface and simulated in GEANT4
- Calibration of cosmic rate and modelling of crucial variables was performed with four-layer demonstrator data
- Studies with four layer configuration show background is well modelled and under control
- **Use cosmic showers simulation to predict background for Run 3 / HL-LHC**



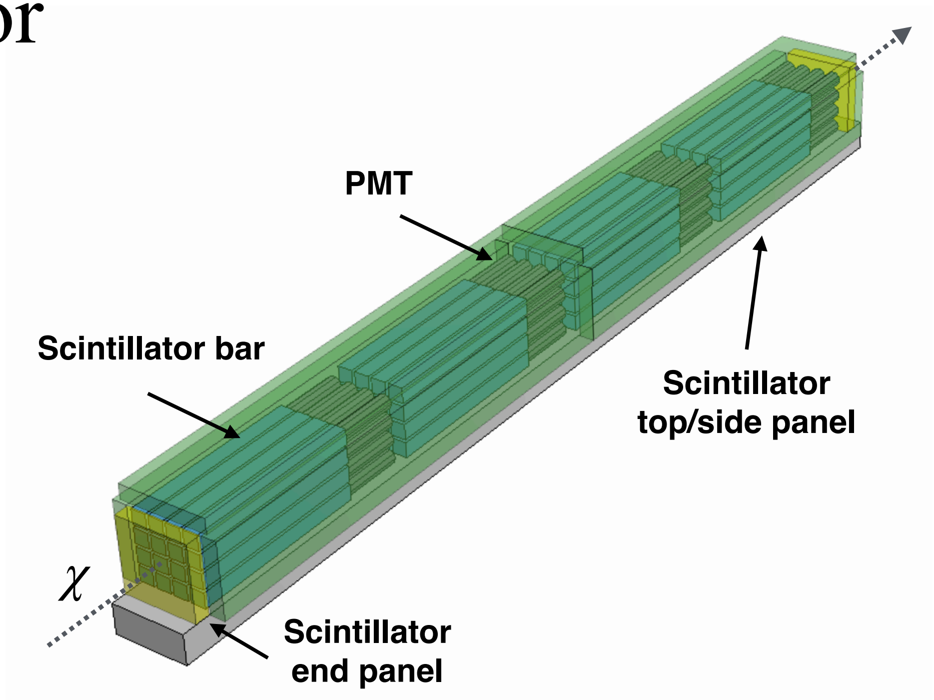


Number of channels across the detector with a detected pulse in cosmic muon events for data (blue) and simulation (red).



The n_{PE} for each pulse in cosmic muon events for data (blue) and simulation (red).

Run 3 Bar Detector



- Two detector designs have been extensively studied for optimised performance
  - **Bar detector**
  - Slab detector

- Bar detector will be the Run 3 upgrade from the milliQan demonstrator
  - expanded size of each layers (4x4 scintillator bars)
  - thicker veto panels, signal amplification, etc.

- Background estimated from simulation of cosmic showers that has been calibrated & validated with data from four-layer demonstrator

Selection	Run 3	HL-LHC
≥ 1 per layer	8.1×10^5	8.2×10^7
$= 1$ Per Layer	6.0×10^3	1.1×10^4
Panel Veto	1.1×10^3	3.1×10^3
Slab Veto	780	3.0×10^3
Four In Line	0.19	2.9×10^{-4}
Max n_{pe}/Min $n_{\mathrm{pe}} < 10$	0.061	9.1×10^{-5}
-15 ns $< \Delta t_{\mathrm{max}} <$ 15 ns	0.012	2.0×10^{-5}
dark rate	0.05	1.4

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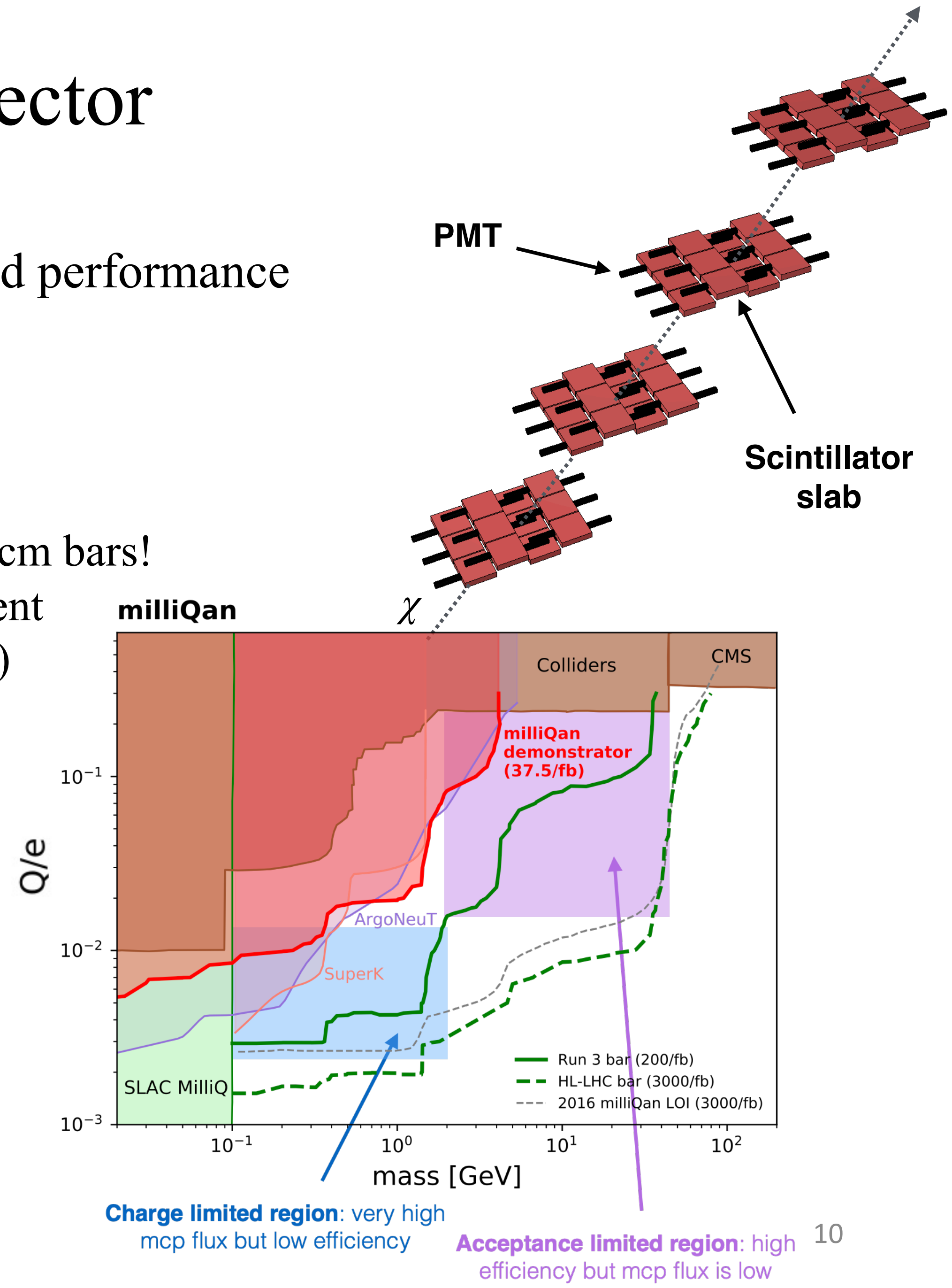
Run 3 Slab Detector

- Two detector designs have been extensively studied for optimised performance
  - Bar detector
  - **Slab detector**
- Slab detector **optimised for acceptance limited region**
  - covers large areas for low cost – same surface area as ~1100 5x5cm bars!
  - innovative four-layer design with 40x60cm slabs in 3x4 arrangement
  - 5cm thick slabs efficient down to Q > 0.01e (≥ 1 PE in each layer)
  - PMTs located at both ends for optimal light collection



Selection	Slab Detector
≥ 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
dark rate ($\lvert\Delta t\rvert < 15$)	0.3
dark rate ($15 < \Delta t < 45$)	0.7

Slabs reject background even without bars!

Detectors Under Construction

- Both bar & slab detectors are currently under construction!
- All components (scintillators, PMTs, etc.) are being tested and will be ready for in-situ assembling by Autumn 2021

Scintillator bars and PMTs are wrapped together in Tyvek to maximise light collection efficiency.

Katia and Sam in the process of assembling a unit of scintillator bar + PMT at UCSB.

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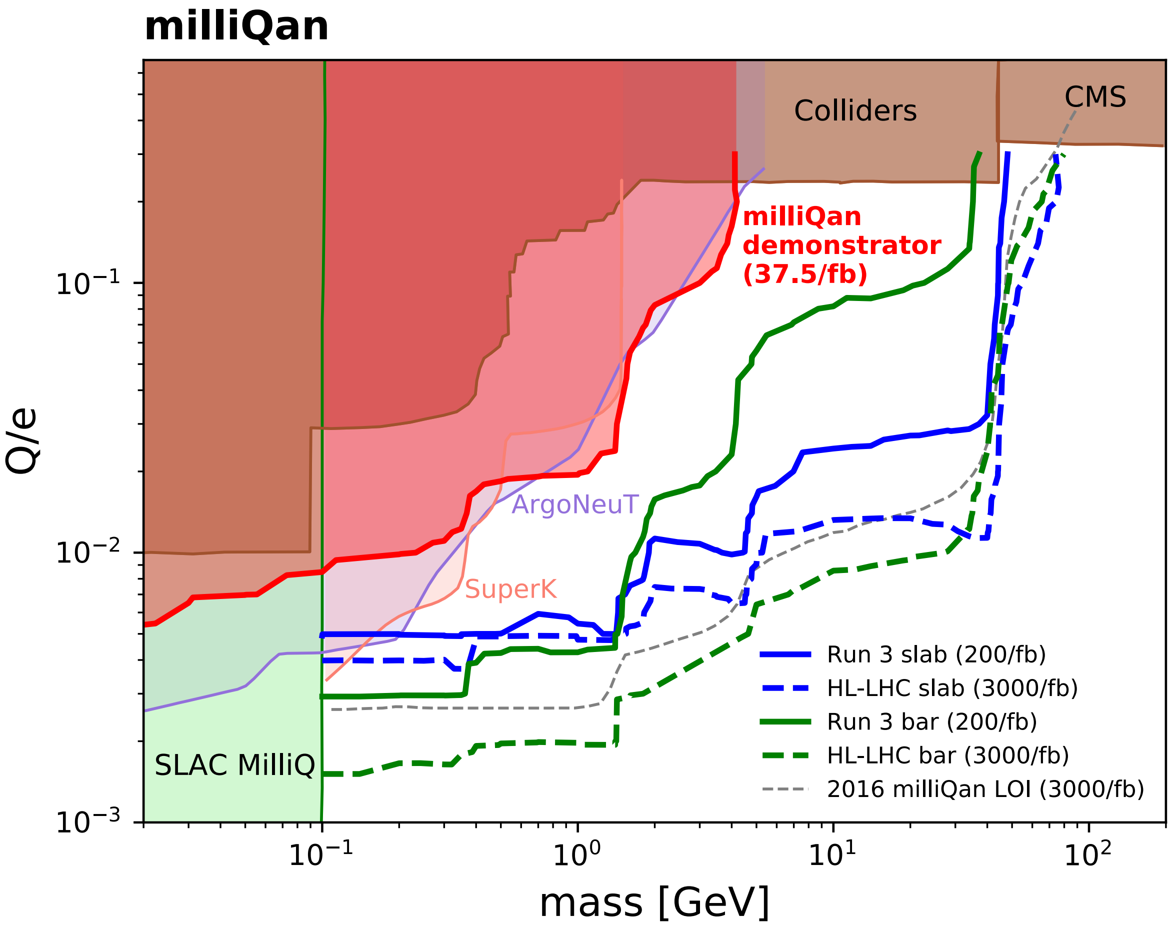
Sensitivity Projections

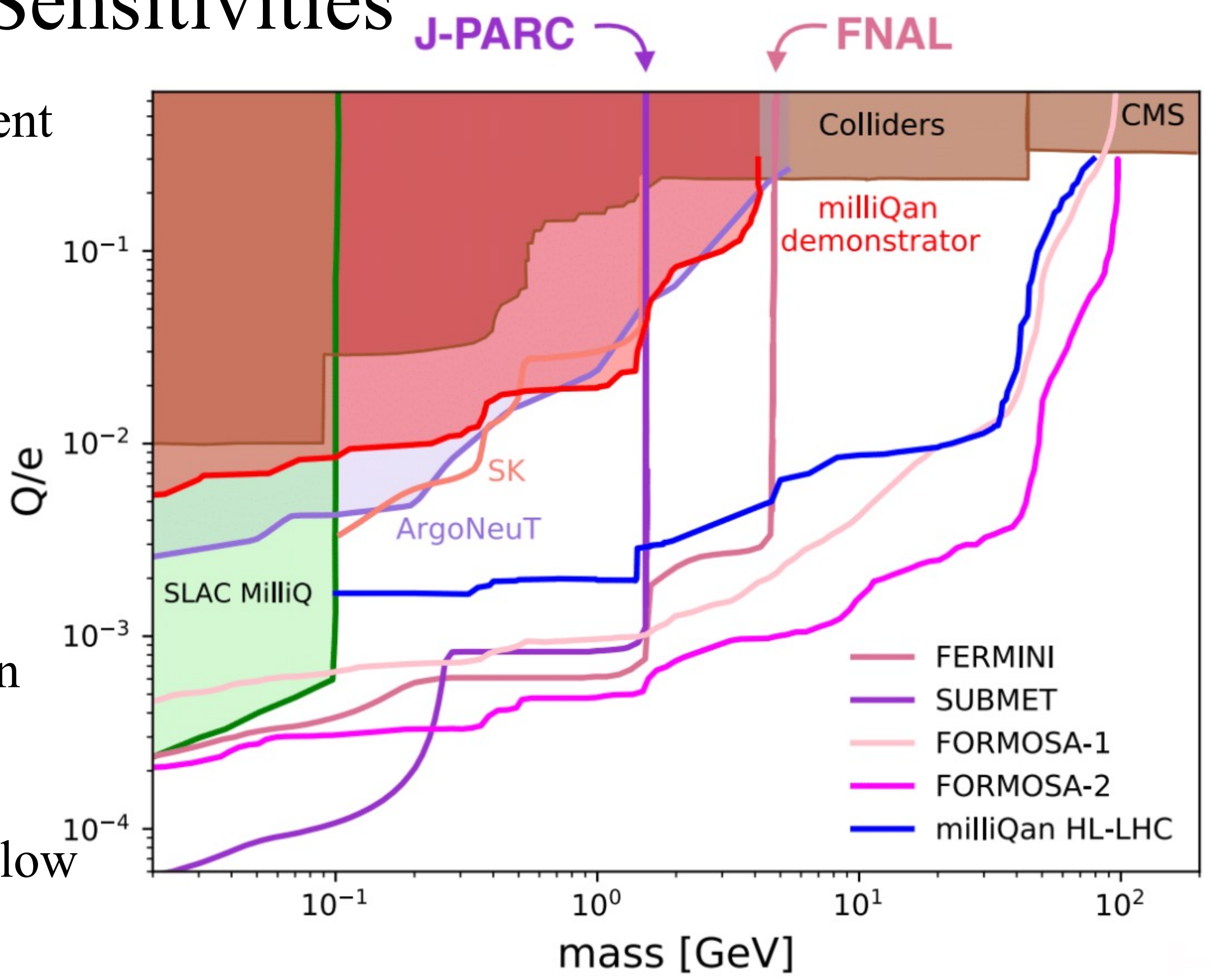
- Experimental design of slab detector **backed up** by guaranteed physics from bar detector
- Slab detector drives sensitivity in acceptance limited region
- Expect world leading sensitivity **for $0.1 < m < 45$ GeV** using a combination of slab and bar detector
- Results also give vital insight into detector designs and backgrounds at alternative locations



- Run 3/HL-LHC sensitivity paper accepted by PRD: arXiv:2104.07151

Future Detector Sensitivities

- Proposed Forward Physics Facility could provide excellent location for a milliQan-like detector
  - mCP rate up to ~250 times larger than current location
  - large muon rates negatively affects trigger efficiency and background rejection (afterpulses)
- Exciting sensitivity prospects in forward region at LHC **if backgrounds under control**
- Exploring possibility of studying forward backgrounds in UJ12 with FASER collaboration
- Neutrino sources provide complementary sensitivity for low mass mCPs
- milliQan results **key** in proving feasibility of all proposals
- Exploring further for snowmass – LOIs 72 & 114



Caveat: FORMOSA lines assume efficient triggering and rejection of beam muon induced backgrounds

milliQan:	2104.07151
FORMOSA:	2010.07941
SUBMET (fully funded):	2007.06329
FERMINI:	1812.03998

Summary

- The milliQan demonstrator ran successfully through 2018 with important insights gained for future detectors
- Secured funding for upgraded milliQan detector layouts
- Bar and slab detectors showed excellent discovery prospects for Run 3 & currently under construction!
- Excellent sensitivity projections from range of complementary millicharged particle detectors at the LHC and neutrino sources

milliQan collaboration

Sensitivity to millicharged particles in future proton-proton collisions at the LHC with the milliQan detector

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(Dated: July 26, 2021)

We report on the expected sensitivity of dedicated scintillator-based detectors at the LHC for elementary particles with charges much smaller than the electron charge. The dataset provided by a prototype scintillator-based detector is used to characterise the performance of the detector and provide an accurate background projection. Detector designs, including a novel slab detector configuration, are considered for the data taking period of the LHC to start in 2022 (Run 3) and for the high luminosity LHC. With the Run 3 dataset, the existence of new particles with masses between 10 MeV and 45 GeV could be excluded at 95% confidence level for charges between 0.003e and 0.3e, depending on their mass. With the high luminosity LHC dataset, the expected limits would reach between 10 MeV and 80 GeV for charges between 0.0018e and 0.3e, depending on their mass.

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Backup

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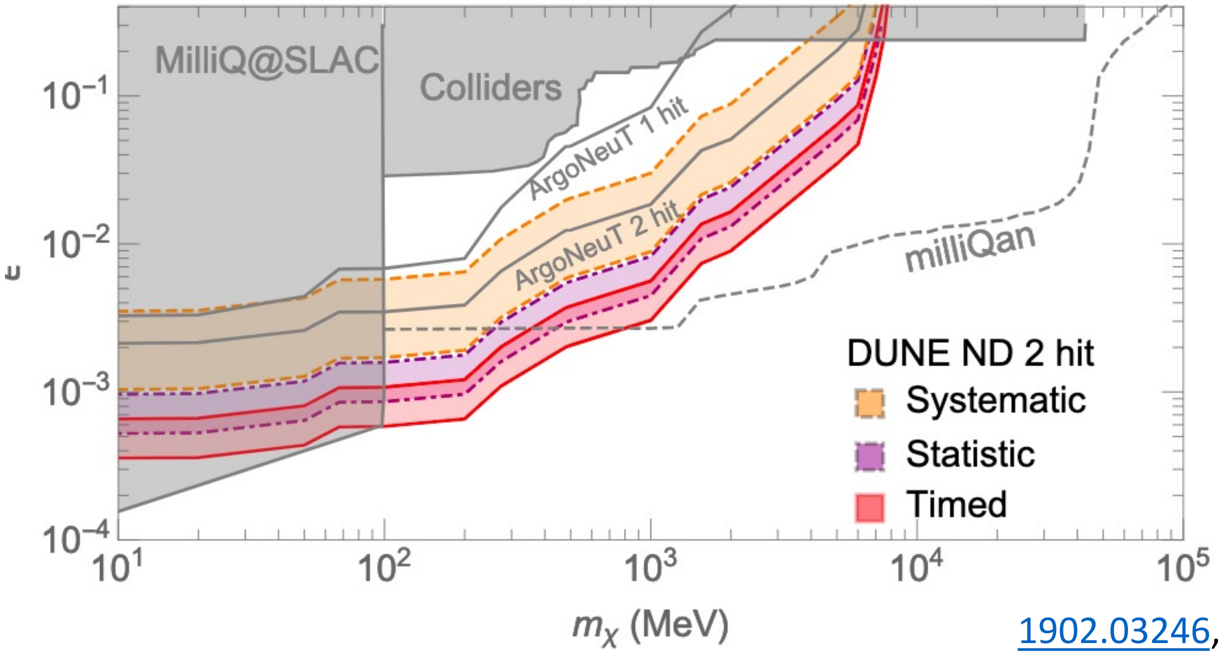
mCP Searches with Neutrino Detectors



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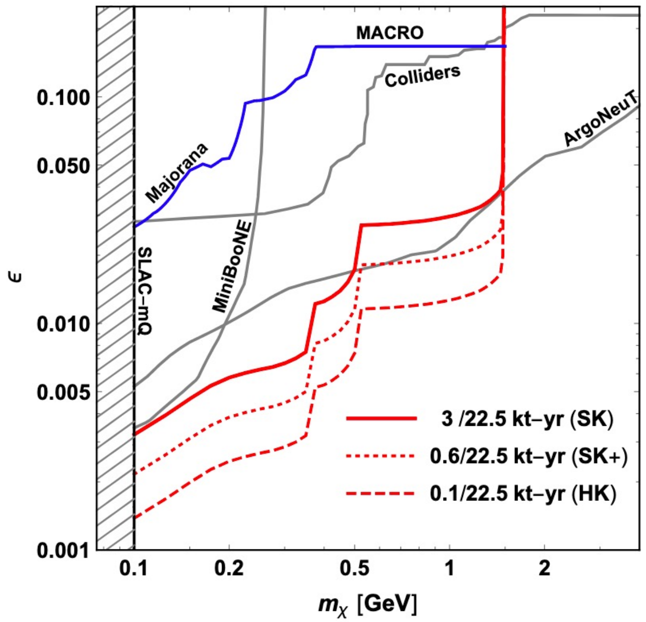
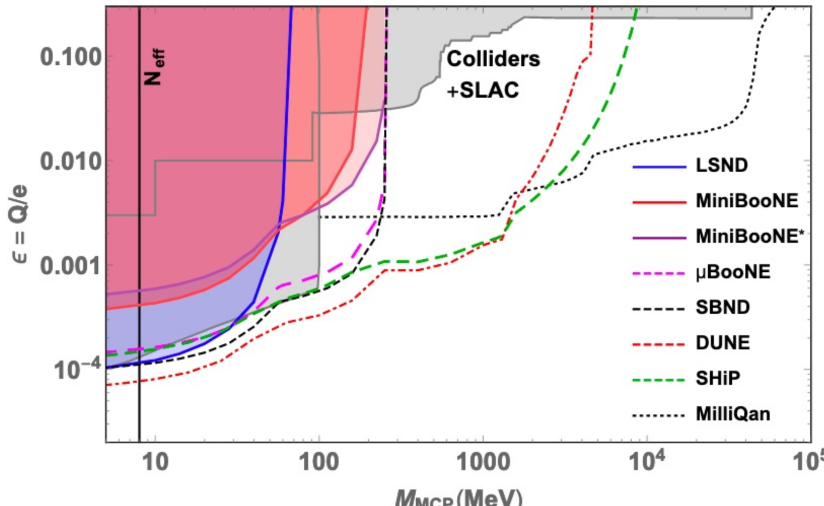
Detection with LarTPC



Production in cosmic ray showers

2002.11732

Fixed source neutrino experiments



1806.03310

- Neutrino detectors provide sensitivity to millicharged particles through hard (>MeV recoil) electron scattering
- Many recent results with complementary sensitivity for low mass mCPs
- Should also be considered in snowmass scope: full consideration of all complementary methods to search for mCPs!

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