Search for Millicharged Particles in pp collisions at $\sqrt{s} = 13\ TeV$:

The milliQan Prototype at the LHC

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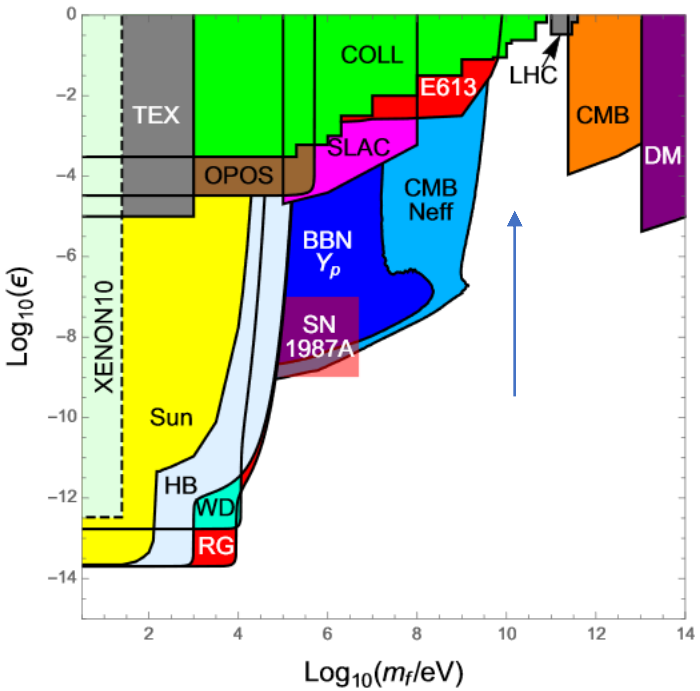
On behalf of the milliQan collaboration

New Perspectives 2020

Searching for mCPs

- Well motivated theoretical justification for millicharged particles
  - Kinetic mixing of dark photons (link to dark sector) would give dark fermions small standard EM charge (arXiv:1506.04760, arXiv:1607.04669v1)
- Copiously produced at existing colliders (LHC):
  - Invisible to general purpose detectors (e.g. ATLAS, CMS), as too little energy is deposited ($E \sim Q^2$)→Need dedicated detectors!
- Scintillator-based searches hinge on idea that scintillators+PMTs would be sensitive to small ionization from mCPs.
  - milliQan (CMS)
  - Proposed: FerMINI (Fermilab, arXiv:1812.03998), SUBMET (J-PARC) → lower energy beams, lower masses
  - Other searches: using neutrino detectors to detect mCPs using electron recoils (arXiv:1902.03246v2, arXiv:1911.07996v3, arXiv:2002.11732v2, arXiv:1806.03310v2) → sensitive to lower masses



From arXiv:1511.01122: different searches of mCPs. Seek to search in the gap of heavier, small-charged particles.

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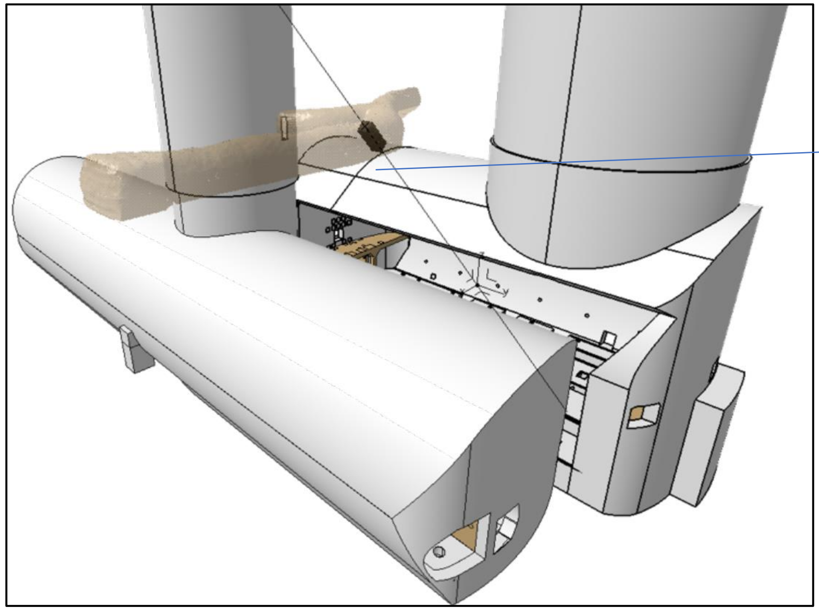
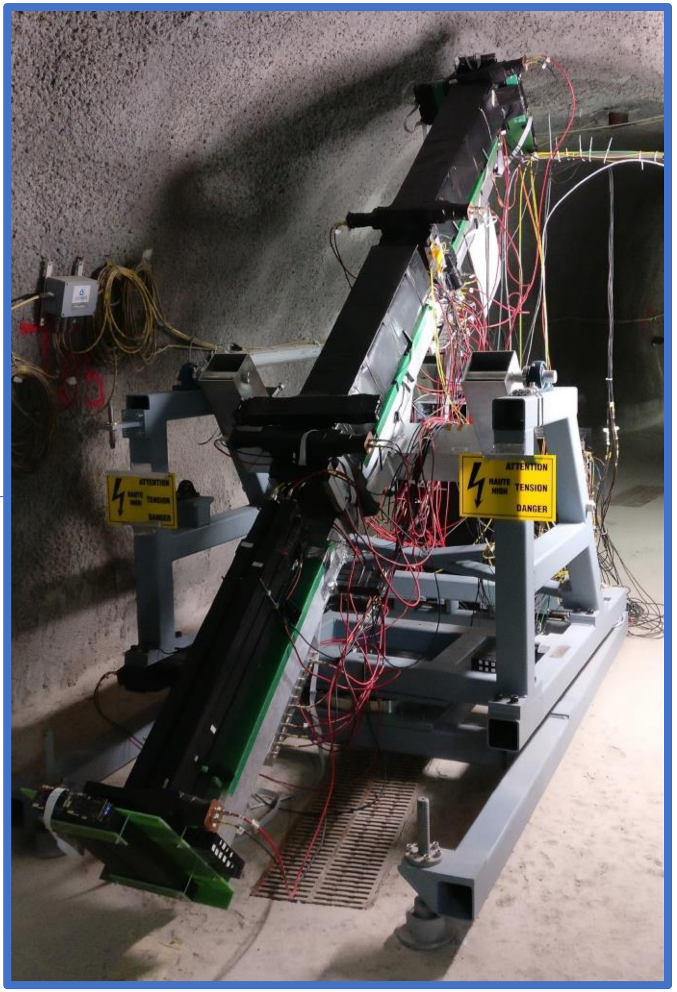
milliQan Demonstrator

- Demonstrator built in 2017 (1% of full detector)
- Existing cavern at CMS
  - 17 meters of rock → reduce beam particles greatly
- Study backgrounds, prove feasibility of experiment
  - 2000+ hrs of data, $35 fb^{-1}$



The CMS caverns

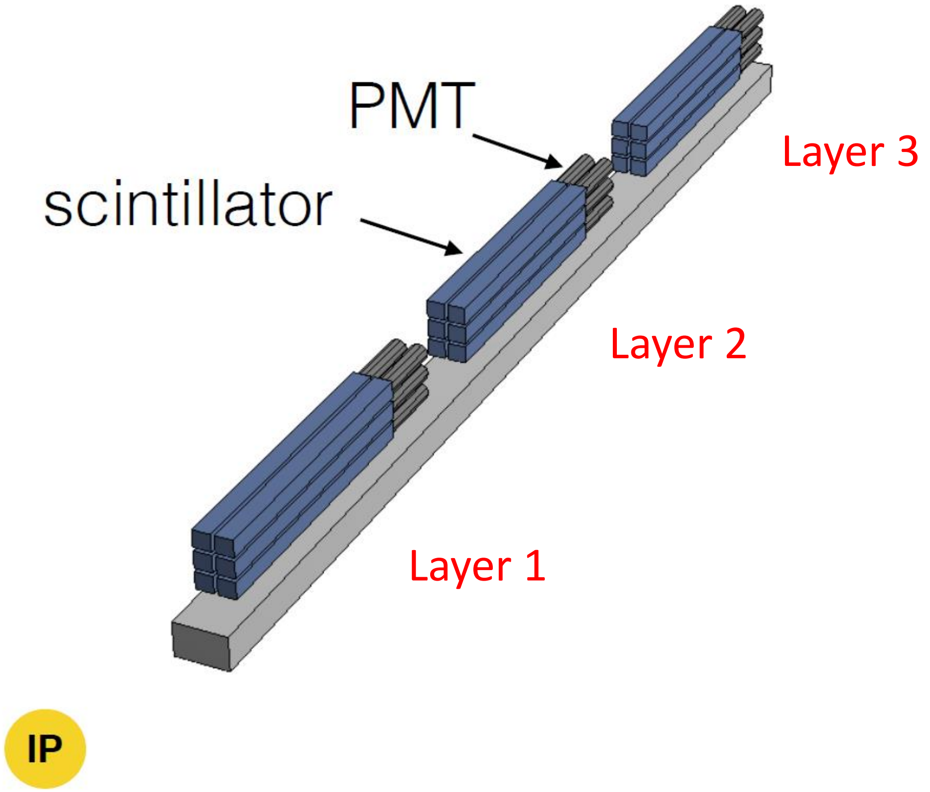
… and the milliQan detector on site



milliQan Demonstrator

Design

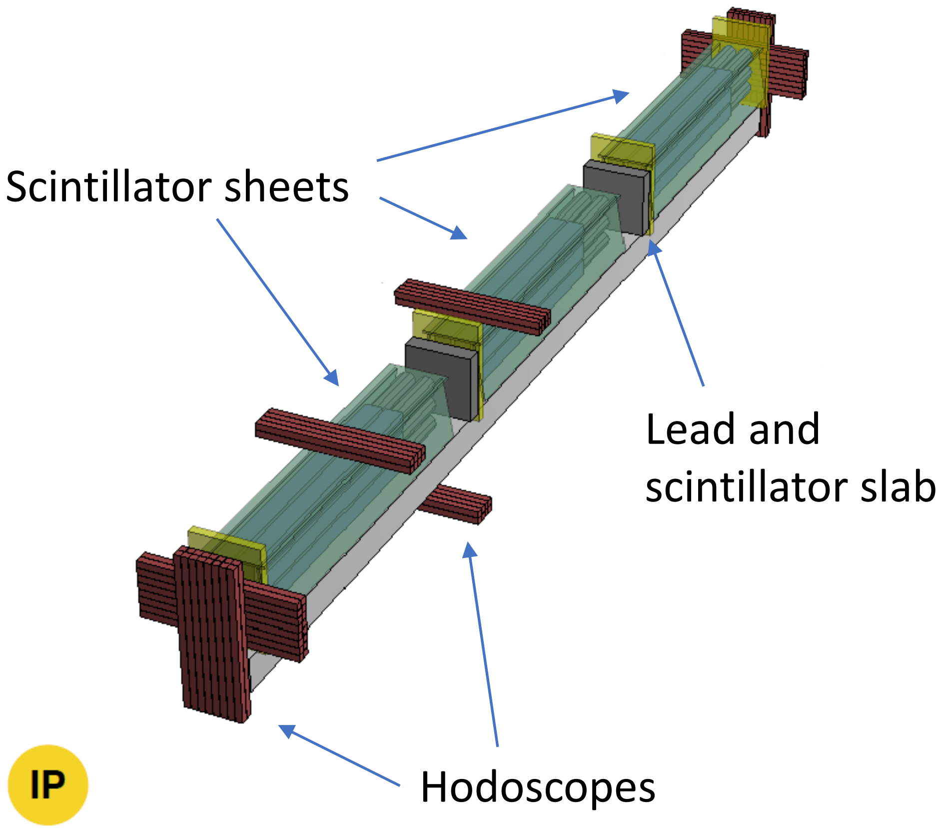
- For small Q (<0.1*e*), need long, sensitive bars to be sensitive
  - Array of 80cm-long scintillator arrays
  - 3 layers of arrays → experience w/ demonstrator changed it to 4 layers
- Layers of bars to reduce background
  - Signal from IP expected to hit 1 bar/layer
  - Trigger on at least 3 channels within 100ns



milliQan Demonstrator

Additional Components

- Lead bricks between layers
  - Stop low energy particles
- Scintillator slabs between layers
  - Tag through going muons
- Thin scintillator panels wrap each layer
  - Reject cosmic muons
- Thin scintillators (hodoscope)
  - Track through-going beam or cosmic muons



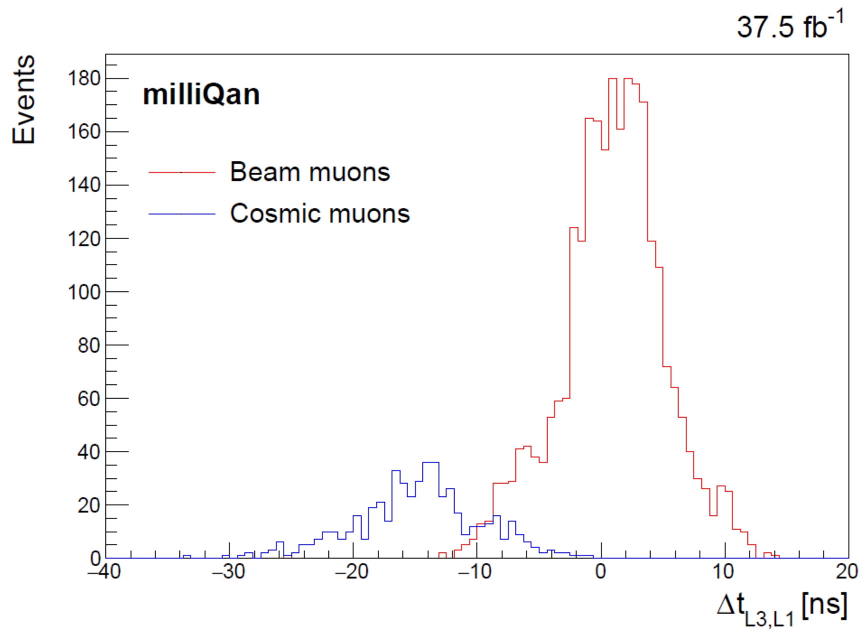
Calibration

Charge Calibration

- Use single Photoelectrons to calibrate PMTs
  - nPE = Pulse area / Mean area of SPE
- Energy deposited scales as Q^2, use cosmic muons to extrapolate
  - <NPE> =1 in the bars for Q/e ~ 0.004-0.007

Timing

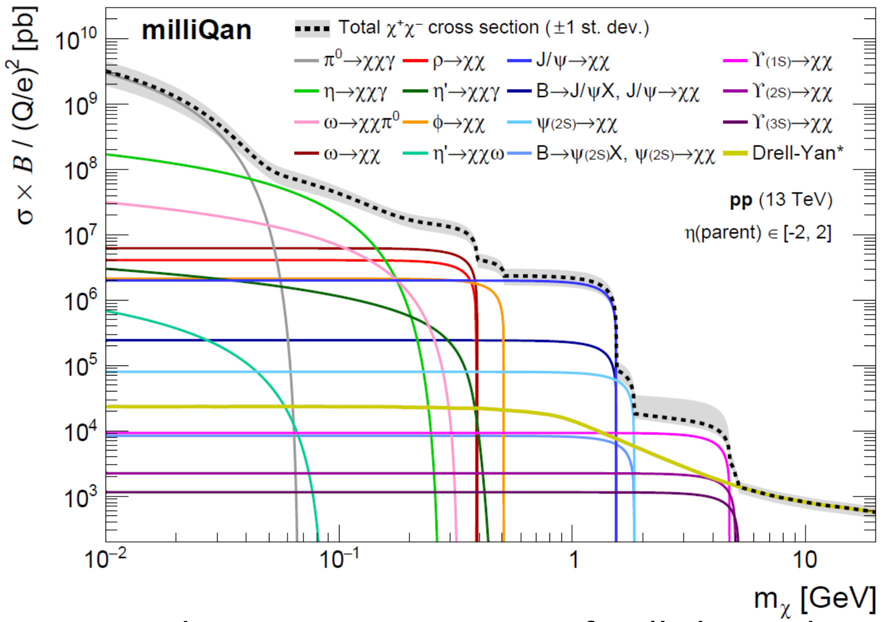
- Use beam and cosmic muons to calibrate PMTs
  - Timing resolution between layers approx. 4 ns
  - Sufficient for 15ns timing selection desired



Time difference, measured in a combination of the beam-on and beam-off data sets, between layer 3 and layer 1 for beam (red) and cosmic (blue) muons that travel through the detector.

Simulation

- Production of mCPs in 13TeV collisions through different processes
  - All relevant processes simulated in that mass range
- Generate beam and cosmic muons
  - Used to validate simulation with data (geometry, rates, energy depositions)
- From generation to full detector simulation in Geant4



Production cross sections of millicharged particles from the processes considered

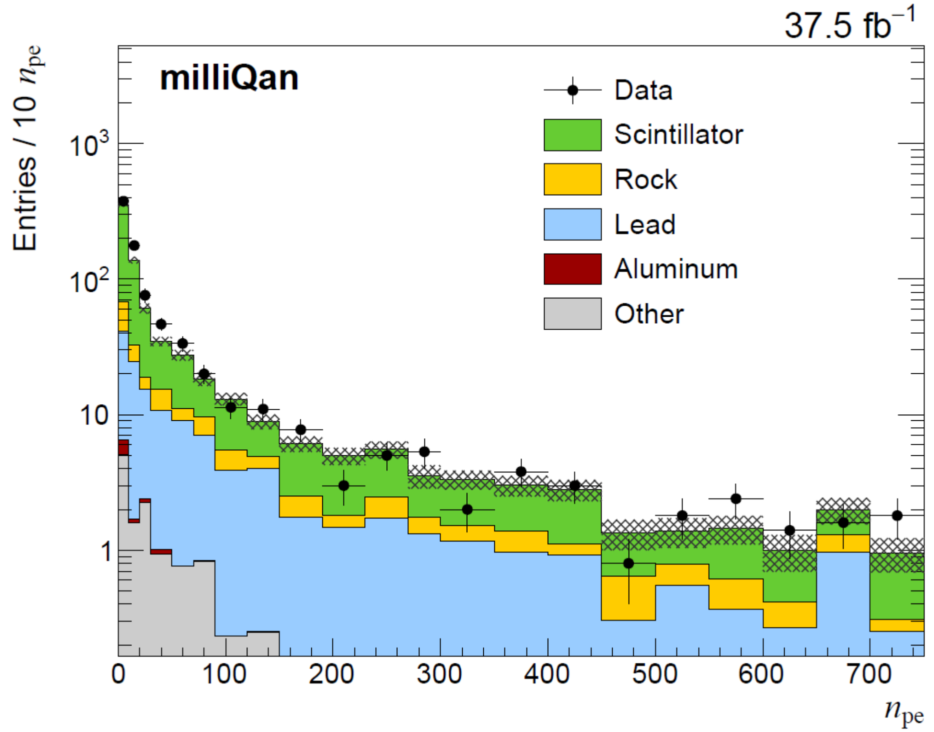
Propagation Schema

Generated Particles → CMS detector material (+ magnetic field) → Rock (17m) → Geant4 Detector Simulation

Simulation

Validation

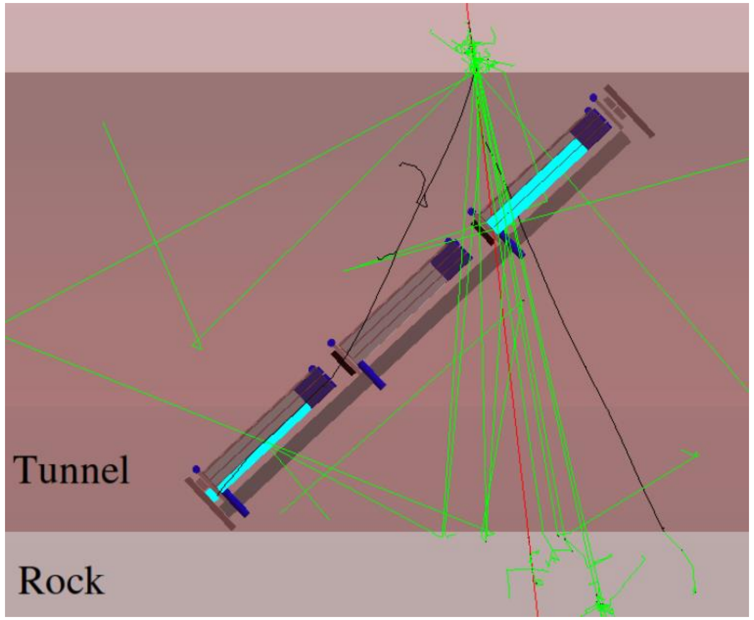
- Simulated and observed beam muon rates agree, angular distribution consistent
- nPE distributions of simulated and observed beam muon agree well across wide range of energies

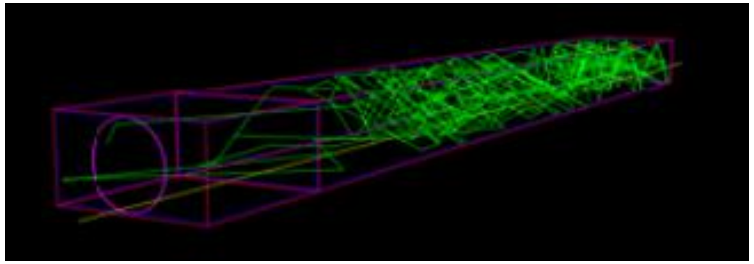


Comparison of data and simulation: Number of photoelectrons deposited due to muon showers

Backgrounds

- Various sources:
  - Dark currents in PMTs → random overlap across layers of dark currents in PMTs or other background + dark current in PMTs
    - Thermal emission of electrons from cathodes in PMTs
  - Cosmic muon showers
    - One muon causing generation of many shower particles (electrons, gammas especially)
  - Radiation in the cavern or materials
  - After pulses in the PMTs
    - Small pulses caused by positive ions generated by the ionization of residual gases in the PMT, can appear up to over few microsec. after initial pulse
- Additional detector components to remove sources of background





Simulated cosmic moun event (muon in red, gammas in green, electrons in black, photons in cyan) and GEANT4 sim, of a scintillator bar

Selections

TABLE I. Sequential impact of each requirement on the number of events passing the selection criteria.

	Selection	Data Beam-on $t = 1106$ h	Data Beam-off $t = 1042$ h	Signal $m_\chi = 0.05$ GeV $Q/e = 0.007$	Signal $m_\chi = 1.0$ GeV $Q/e = 0.02$	Signal $m_\chi = 3.0$ GeV $Q/e = 0.1$
Common	≥ 1 hit per layer	2 003 170	1 939 900	136.4	34.2	5.7
Selections	Exactly 1 hit per layer	714 991	698 349	123.1	31.0	5.0
	Panel veto	647 936	632 494	122.5	30.8	4.9
	First pulse is max	418 711	409 296	114.3	30.6	4.8
	Veto early pulses	301 979	295 040	113.9	30.6	4.8
	max n_{pe} / min $n_{\mathrm{pe}} < 10$	154 203	150 949	104.2	29.6	4.7
	$\Delta t_{\mathrm{max}} < 15$ ns	5 284	5 161	72.8	28.4	4.4
	Slab muon veto	5 224	5 153	72.8	28.4	4.4
	Straight path	350	361	68.4	28.1	4.2
	$\mathrm{N_{slab}} = 0$	332	339	64.8	16.9	0.0
	$\mathrm{N_{slab}} \geq 1$	18	22	3.6	11.2	4.2
SR 1	$\mathrm{N_{slab}} = 0$ & min $n_{\mathrm{pe}} \in [2, 20]$	129	131	47.4	0.4	0.0
SR 2	$\mathrm{N_{slab}} = 0$ & min $n_{\mathrm{pe}} > 20$	52	45	0.0	16.5	0.0
SR 3	$\mathrm{N_{slab}} = 1$ & min $n_{\mathrm{pe}} \in [5, 30]$	8	9	1.1	0.5	0.0
SR 4	$\mathrm{N_{slab}} = 1$ & min $n_{\mathrm{pe}} > 30$	4	4	0.0	8.7	0.0
SR 5	$\mathrm{N_{slab}} \geq 2$	1	1	0.0	2.0	4.2

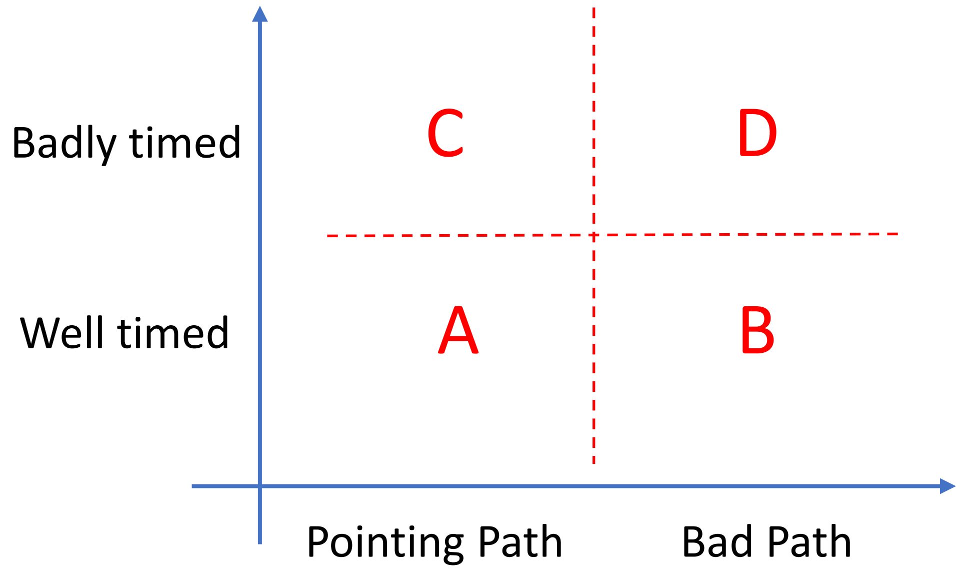
Data

Generated signal

- **Primarily**: one hit in each of the 3 layers in a straight path (from IP) within 15 ns.
  - Dominant background rejections
- **Other cuts**: veto in the scintillator slabs, slabs between layers, veto afterpulses, veto events with large discrepancies between bar nPEs

Different **Signal Regions** (SR) to be sensitive to different ranges of signal

ABCD Method



ABCD Method classification regions. Straight path from IP signifies one hit per layer with same row and column, good timing means hits within 15ns.

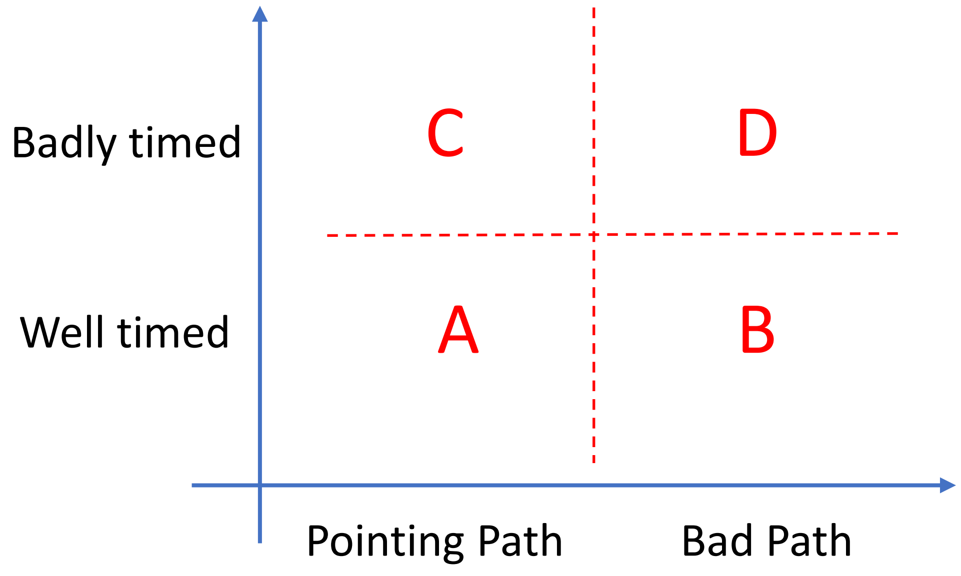
- Time and path independent variables for one hit per layer, **background**, events: can be used to predict background
  - Correlated in signal events

$$\frac{A}{B} = \frac{C}{D} \Rightarrow A = \frac{B * C}{D}$$

- A is the signal region → well timed, pointing path
- Works well for **beam-off data**, define **systematic** uncertainty:
  - Backgrounds don't come from beam processes but from slide 9 events, so we can validate on beam-off data

Region	N_{slab}	min n_{pe}	Prediction	Observation	Systematic
1	0	[2,20]	$121.2^{+6.0}_{-5.9}$	131	8%
2	0	> 20	$47.4^{+5.2}_{-4.8}$	45	5%
3	1	[5,30]	$7.8^{+2.5}_{-1.8}$	9	15%
4	1	> 30	$2.7^{+2.1}_{-1.1}$	4	48%
5	≥ 2	-	$0.8^{+1.4}_{-0.4}$	1	25%

ABCD Method



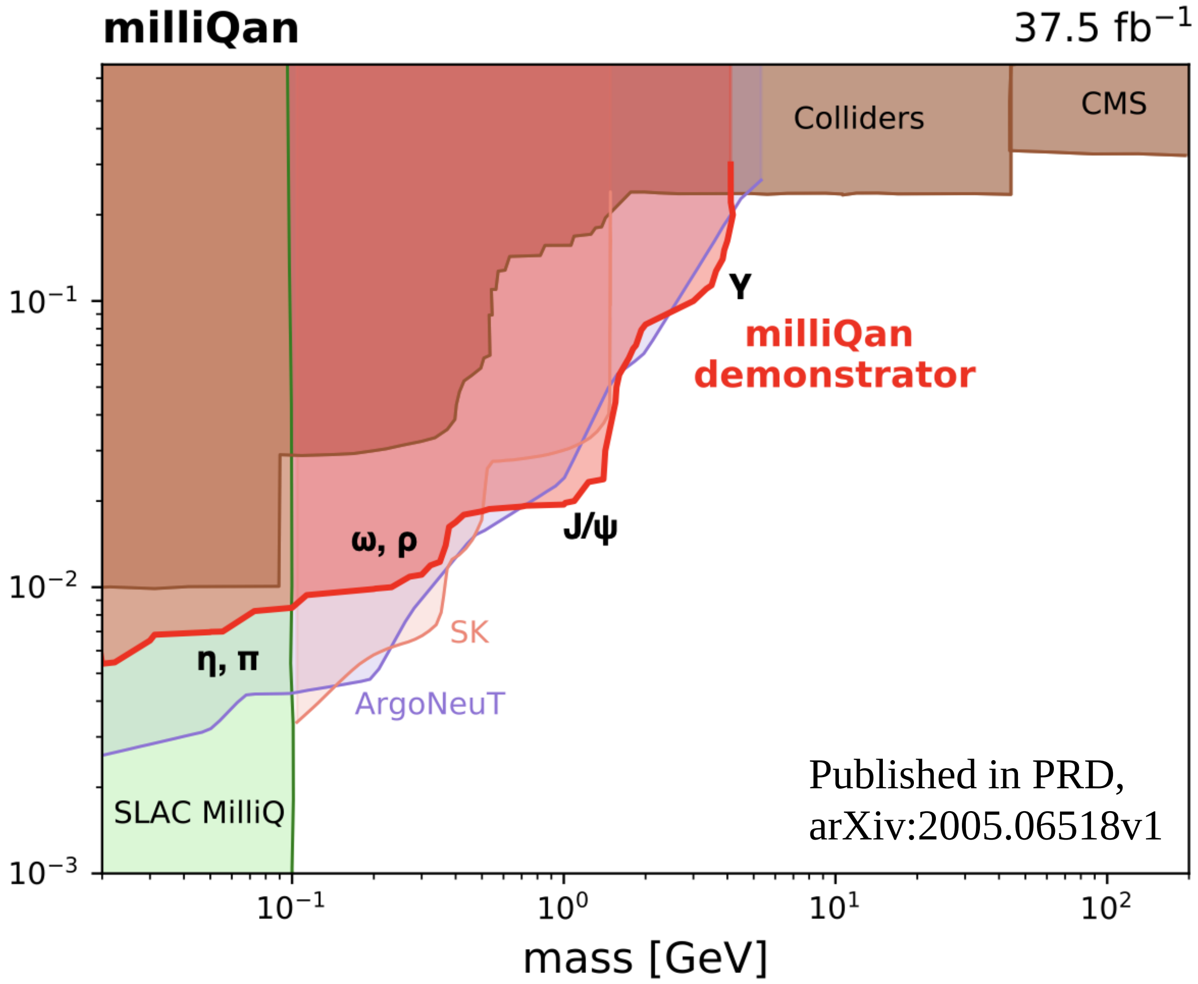
ABCD Method classification regions. Straight path from IP signifies one hit per layer with same row and column, good timing means hits within 15ns.

ABCD predictions and observed events for **beam-on** data in each signal region:

Region	N_{slab}	min n_{pe}	Prediction	Observation
1	0	[2,20]	124^{+11}_{-11}	129
2	0	> 20	$49.9^{+6.0}_{-5.4}$	52
3	1	[5,30]	$10.7^{+3.6}_{-2.6}$	8
4	1	> 30	$2.4^{+2.1}_{-1.1}$	4
5	≥ 2	-	$0.0^{+0.9}_{-0.0}$	1

➔ Consistent in all regions

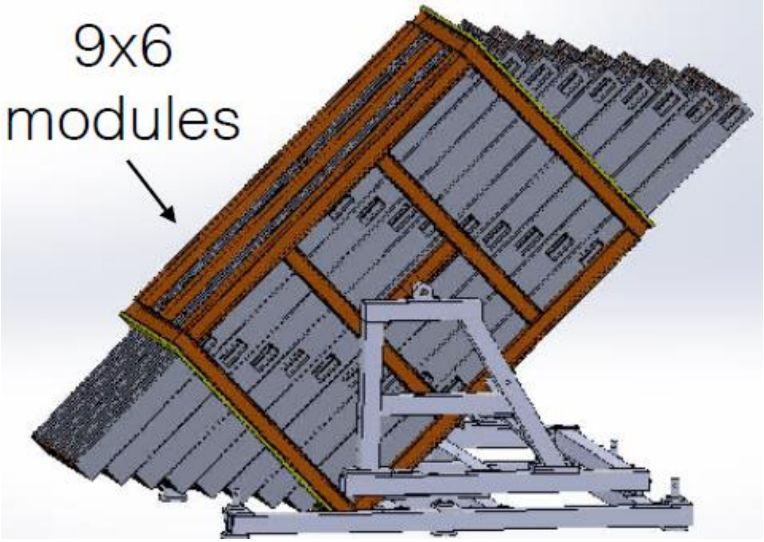
Interpretation

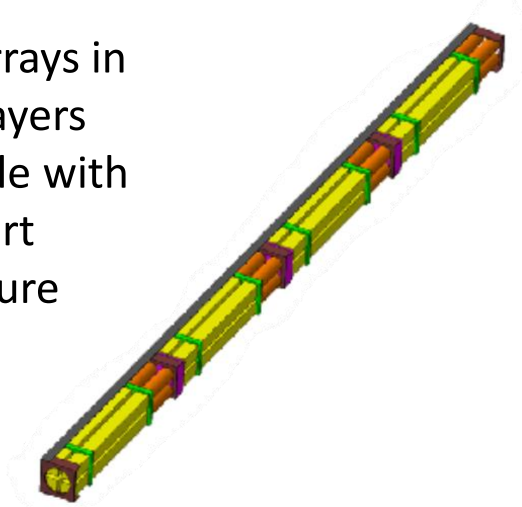


- Exclusion at 95% confidence level
  - Demonstrator (1% of full design) already competitive! Published in PRD
  - Constraints on mCPs for M ∈ [20,4700] MeV, Q/e ∈ [0.006, 0.3]
- Demonstrator experience:
  - Correlated activity (cosmics, radiation, etc.) important source of background
  - Fourth layer added to full detector design to reduce both backgrounds.
  - Fourth layer designed in reducing background validated in dedicated runs (~300 factor reduction)

Future Plans

- Invest in better PMTs, four layer design, full detector plans mature
  - Two adjacent detectors of 864 bars in total in 4 layers
- Working on new paper with updated projections for full detector
- For Run 3, based on successful running of demonstrator, won Harvey L. Karp Discovery Award for the expansion of the detector
  - Enough funding for a 4x4x4 detector
  - Important steppingstone on way to full detector
  - Guaranteed physics coming up!





2x2 arrays in four layers module with support structure

THE MILLIQAN EXPERIMENT

- The milliQan detector can provide **unique sensitivity** to millicharged particles
- Built, commissioned and operated small prototype to **prove feasibility** and **measure backgrounds** rate for full detector
- Signal generation, propagation and detector response **fully simulated**
- Search for millicharge particles with prototype achieves **competitive constraints**
- **Mature mechanical** design for full detector
- **Secured funding** for substantial upgrade for Run 3, but still **actively seeking funding to install detector** for upcoming runs of the LHC for the expansion to the full detector

Collaboration

Search for millicharged particles in proton-proton collisions at $\sqrt{s} = 13$ TeV

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Projections paper to come out soon!