milliQan: a search for milli-charged particles at the LHC

Bennett Marsh
on behalf of the milliQan collaboration

November 22, 2019
Light Dark Matter @ Accelerators Workshop

Why milli-charged particles?

No signs of dark matter or other new physics at the LHC

What kind of new physics might we be missing? Standard model extensions with **dark or hidden sectors** may produce signatures not caught by present experiments

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Why milli-charged particles?

- Dark sector can be introduced into the SM with the addition of a "dark photon" A', that couples to a massive "dark fermion" ψ' with strength e'

$$\mathcal{L}_{\text{dark-sector}} = \underbrace{-\frac{1}{4}A'_{\mu\nu}A'^{\mu\nu}}_{\text{massless "dark photon"}} + \underbrace{i\bar{\psi}'(\gamma^\mu\partial_\mu + ie'\gamma^\mu A'_\mu + iM_{\text{mCP}})\psi'}_{\text{"dark fermion" with mass } M_{mCP}\text{, charge } e'} - \underbrace{\frac{\kappa}{2}A'_{\mu\nu}B^{\mu\nu}}_{\text{mixing term } (\kappa << 1)}$$

- Small mixing term between A' and weak hypercharge B provides a **link to SM**
- Standard gauge transformation $A'_\mu \to A'_\mu + \kappa B_\mu$ eliminates mixing term, and introduces a coupling between ψ' and B via $\overline{\psi'}\kappa e'\gamma^\mu B_\mu \psi'$
- **So ψ' couples to SM photon with charge** $\kappa e' \cos\theta_W \to$ **milli-charged particles (mCPs)**

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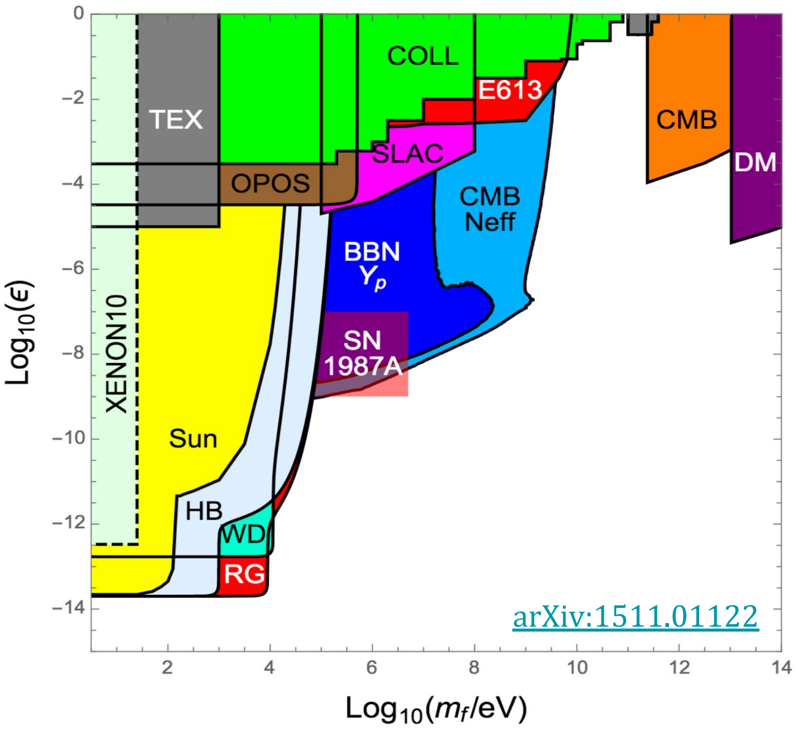
Status of searches



arXiv:1511.01122

Large variety of searches via colliders, solar effects, astronomical observations, and cosmological bounds cover a wide range of masses and charges

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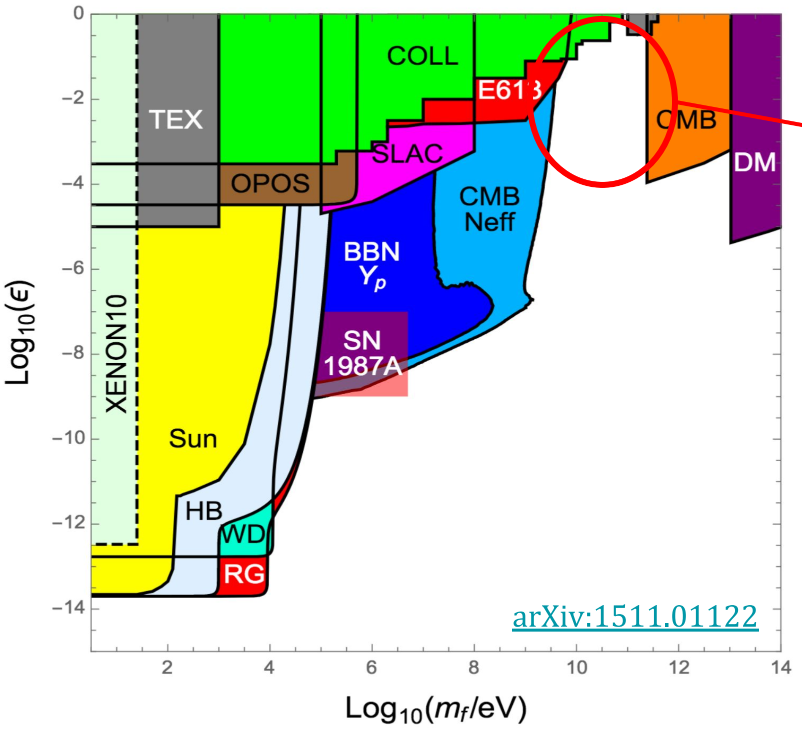
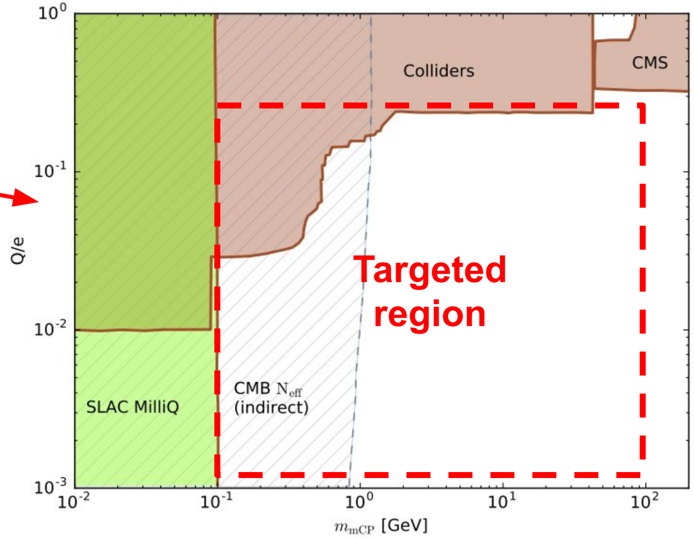
Status of searches





Gap at high mass and charge between 10^{-3} and 10^{-1} e

Can target with a dedicated experiment at the LHC!

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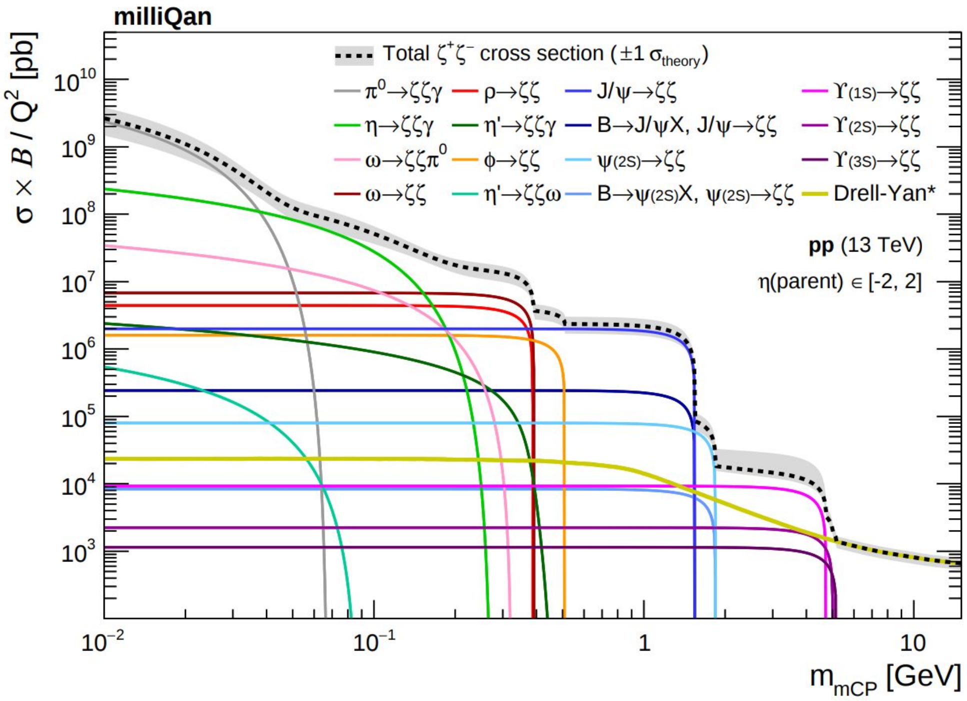
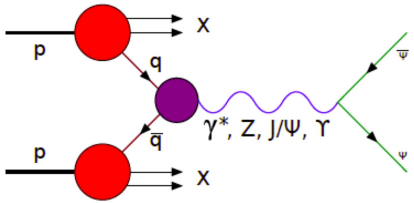
mCP production at the LHC



- Any process that produces an e^+e^- pair via a virtual photon can also produce an mCP pair
- Branching ratios can be computed as functions of mass/charge (scales as Q^2)
- Low masses dominated by QCD production of π^0, η, ρ, ω, ϕ
- Masses near 1 GeV dominated by J/ψ decays, then Y's past 1.5 GeV
- Past 5 GeV, production is purely Drell-Yan



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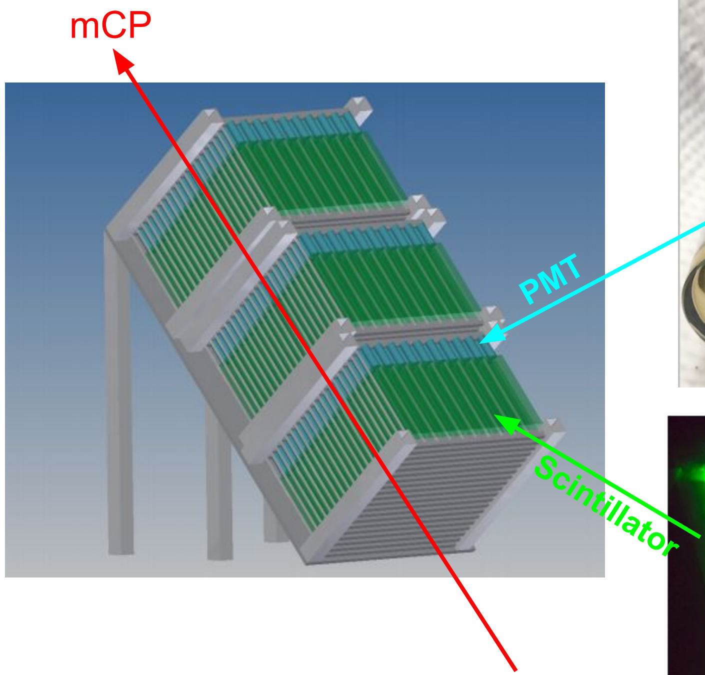
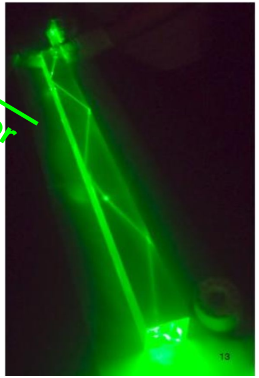
milliQan concept

- Array of **scintillator bars** coupled to **PMTs** that can detect individual photoelectrons produced by through-going milli-charged particles
- Key concept is the **three-layer design**, requiring simultaneous hits in all three layers – drastically cuts down on backgrounds
- Signal would appear as a handful of in-time photoelectrons in three bars in a straight-line path





LOI (2015): arXiv:1607.04669

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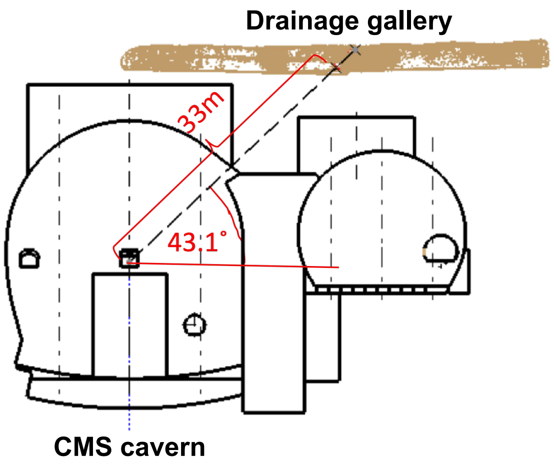
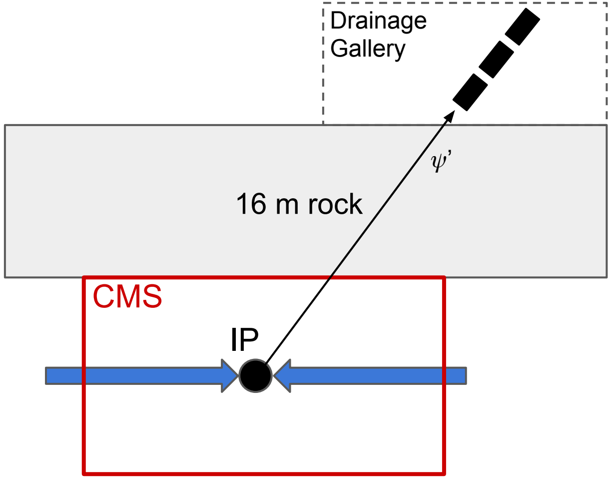
milliQan location

- Placed in an existing **drainage gallery** above the CMS experimental cavern at the LHC
- Located 33 m from interaction point at η ~ 0.1, with 16 m of rock that naturally shields experiment from beam-based particles





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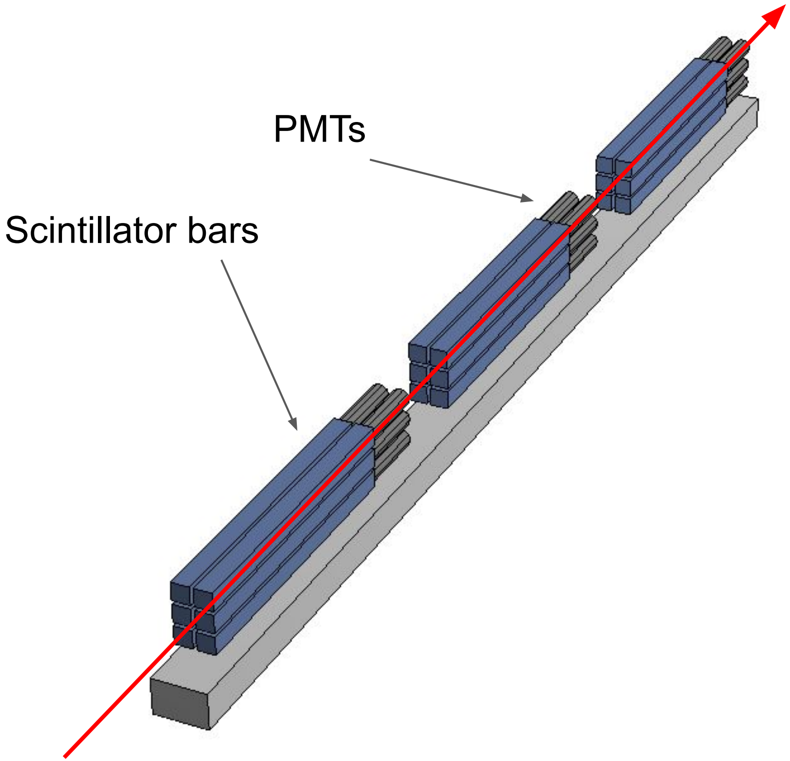
milliQan demonstrator



- In 2017/18, a smaller **demonstrator** was installed as a proof-of-concept and to study backgrounds
- 3 layers of 2x3 scintillator bar arrays (~1% of full milliQan)

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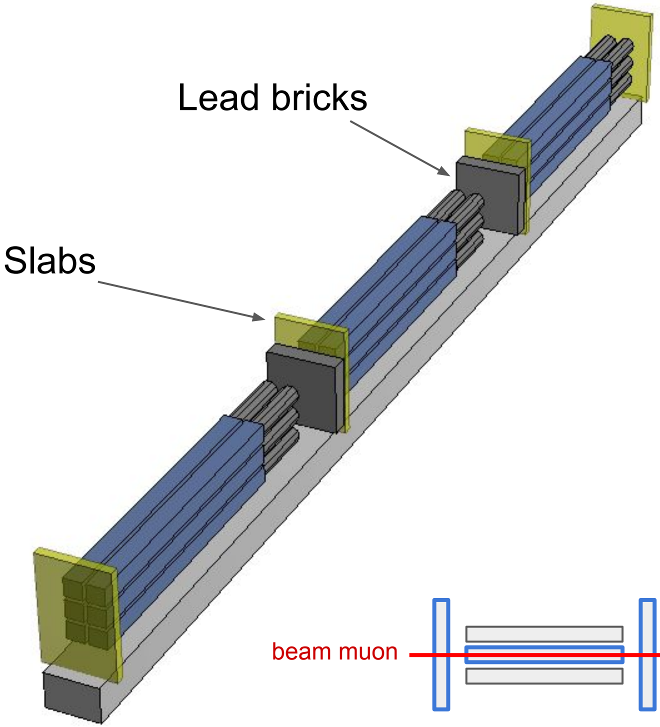
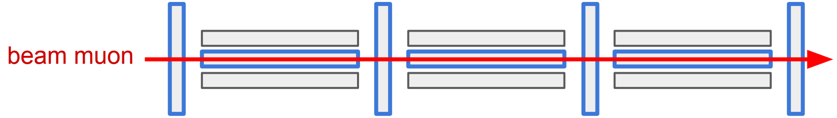
milliQan demonstrator





- In 2017/18, a smaller **demonstrator** was installed as a proof-of-concept and to study backgrounds
- 3 layers of 2x3 scintillator bar arrays (~1% of full milliQan)
- Scintillator **slabs** to tag through-going particles and **lead bricks** to shield radiation

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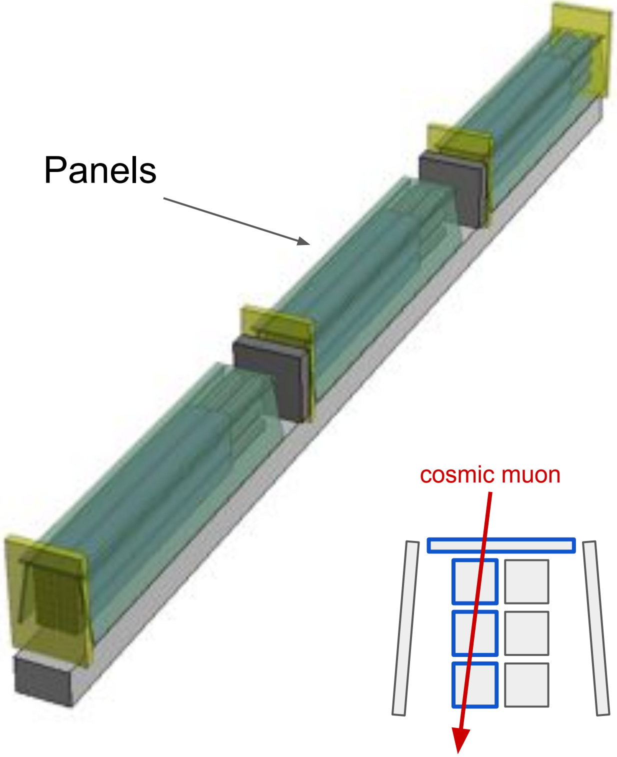
milliQan demonstrator



- In 2017/18, a smaller **demonstrator** was installed as a proof-of-concept and to study backgrounds
- 3 layers of 2x3 scintillator bar arrays (~1% of full milliQan)
- Scintillator **slabs** to tag through-going particles and **lead bricks** to shield radiation
- 3 scintillator **panels** covering each layer to tag cosmic muons

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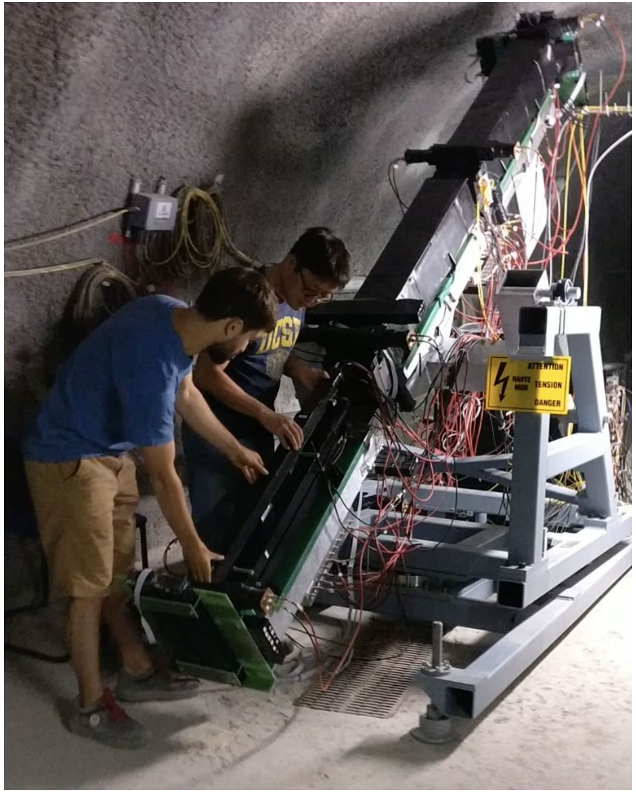
milliQan demonstrator



- Placed on a custom-built aluminum stand, aligned by CERN team to point at interaction point
- Successfully collected **~37 fb^{-1}/2000h** of beam-on data in 2018 (plus lots of beam-off data)
- Fully simulated in Geant4 to compare measured data to predictions
- Many results so far in checking alignment, calibrating time and PMT response, and measuring backgrounds

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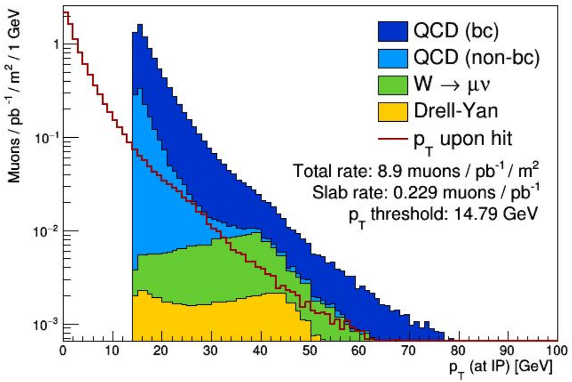
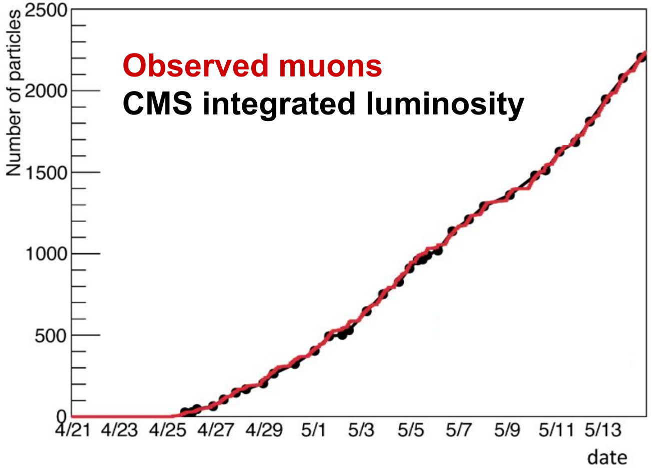
Muons from the LHC

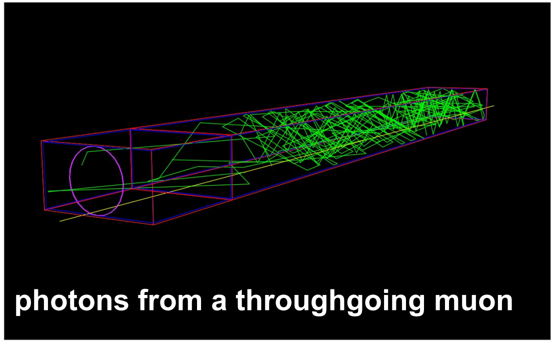
- Rock shields the experiment from most beam-based particles, but muons with energy above ~15 GeV can make it to the detector
- Appear as large in-time pulses in all 4 slabs
- Also predict rate from simulation, by generating muon decays and propagating through a model of CMS magnetic field and material map
- Predicted rate from **simulation** is **0.25 ± 0.08 / pb^{-1}** (primary uncertainties from the B-hadron cross section and amount of material between IP and detector)
- Observed rate in **data** is **0.18 / pb^{-1}**
- **Angular distribution** of muons is also validated

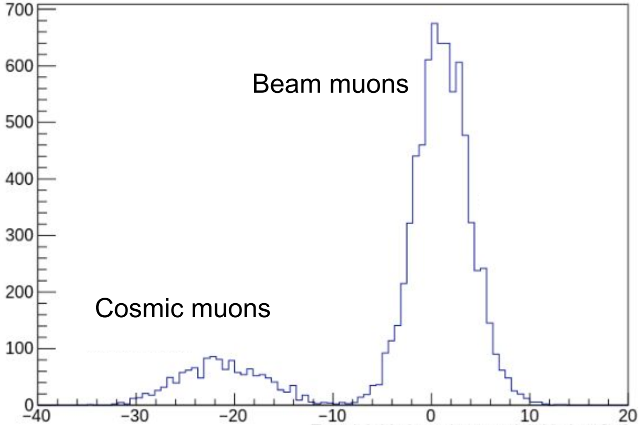




Calibration

- **Charge calibration**
  - Important to obtain a per-channel measurement of the number of observed PE per incident particle charge/distance traversed
  - Individual PMT responses calibrated using afterpulses (checked with LED bench tests)
  - Scintillators calibrated with vertical cosmics
- **Time calibration**
  - Must account for geometry, cable length, PMT rise time
  - Calibrated using beam/cosmic muons
  - Time resolution of **4 ns** achieved





Δt(top slab, bottom slab)

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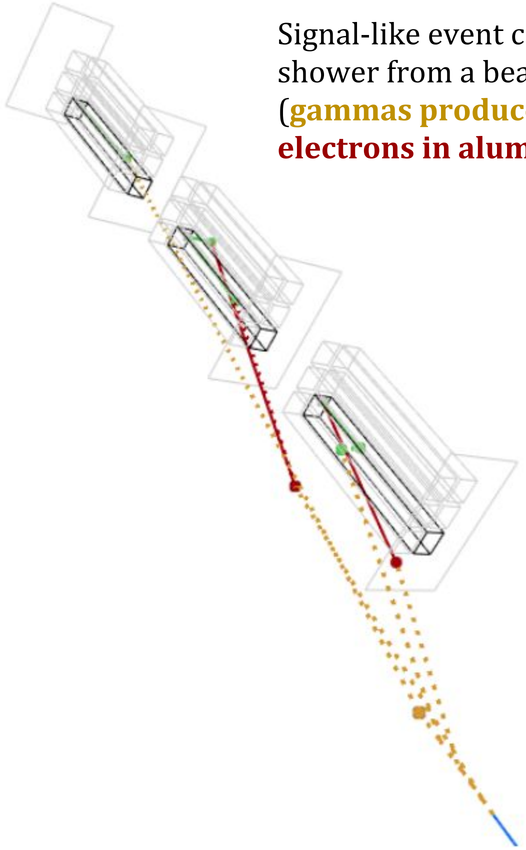
Backgrounds

- Backgrounds come from 3 in-time hits from either the same process or a mixture of processes
  - PMT dark rate
  - Afterpulses
  - Radiation
  - Showers from beam/cosmic muons
- Important lesson from demonstrator: **PMT dark rate is a subdominant background source**
- Suggests that further background suppression can be achieved with extra shielding/tagging of external sources



Signal-like event coming from a shower from a beam muon (**gammas produced in rock** and **electrons in aluminum support**)

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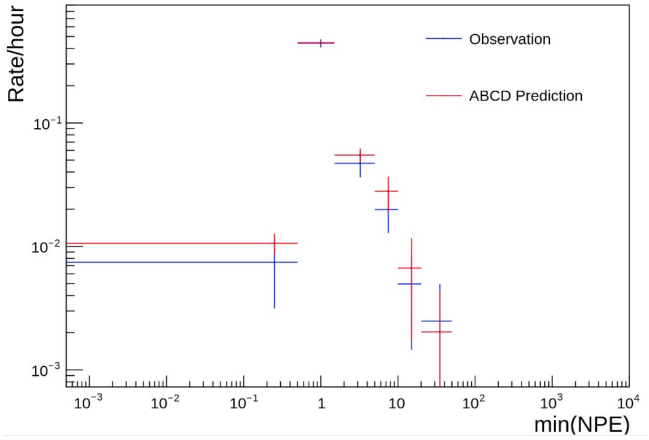
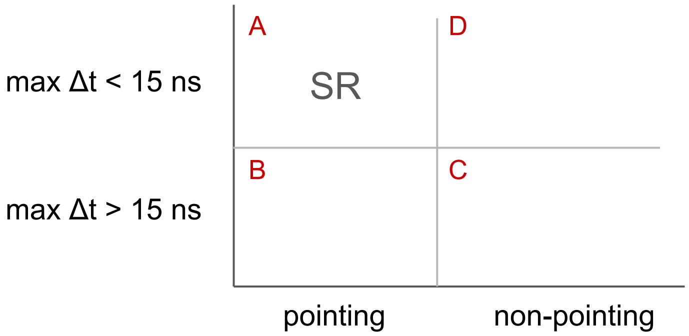
Background prediction

- Background prediction is performed using a data-driven ABCD method from various control regions
- Use signal-depleted control regions from inverting **pointing** or **in-time** requirements
- Validated in **beam-off** data and in **simulation** (for backgrounds from beam/cosmic muons)





$$N_A = \frac{N_B}{N_C} N_D$$

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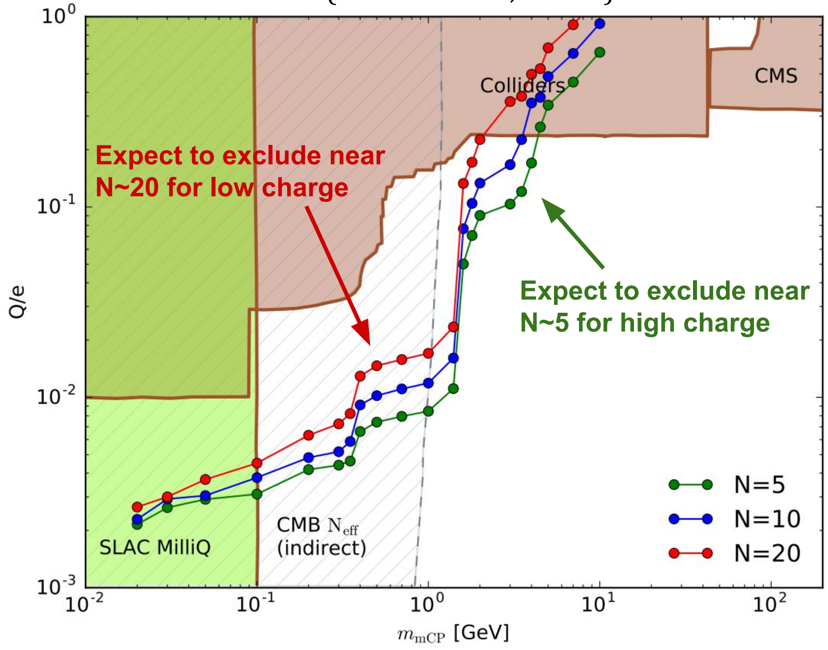
Signal simulation

- Individually generate mCP decays from all relevant production processes (light mesons, J/ψ, upsilon, DY)
- Propagate through model of CMS material/B-field
- Feed into Geant simulation of demonstrator, and inject simulated photoelectron pulses into zero bias data to emulate real signal

Contours of constant expected yield
(demonstrator, 37 fb^{-1})



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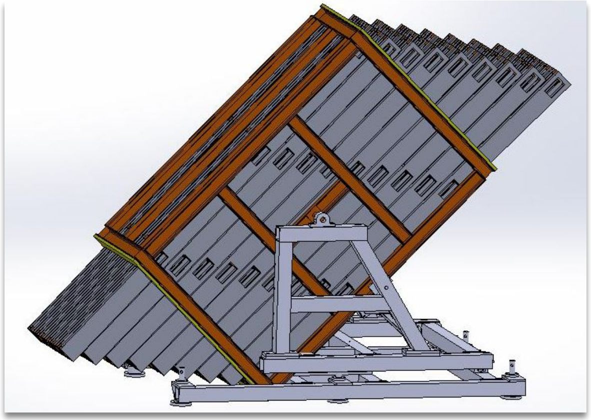
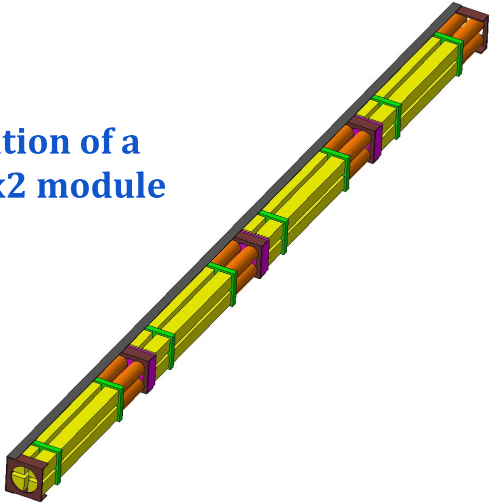
Plans for full detector

- Plans for final mechanical structure finalized with **four layers** to further reduce background
- Due to space constraints, use two adjacent detectors each composed of a 9x6 array of “modules”, each composed of four 2x2 layers





Composition of a single 2x2 module

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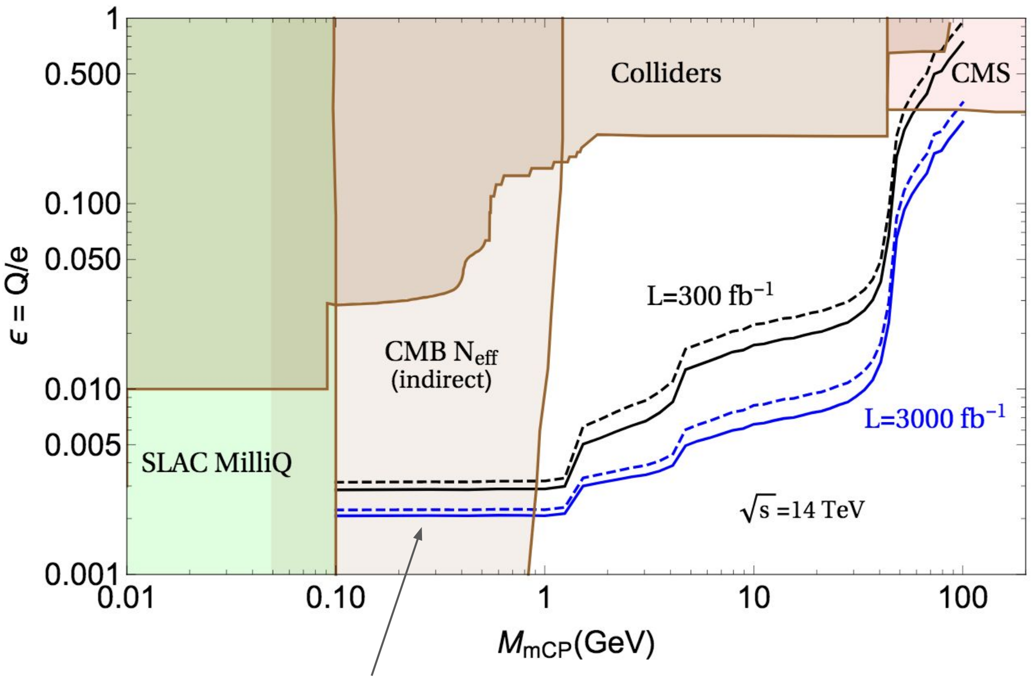
Full detector expected sensitivity



Flattening artificial here, as light meson QCD production was not simulated

From 2015 LOI -- updated full detector projection coming soon

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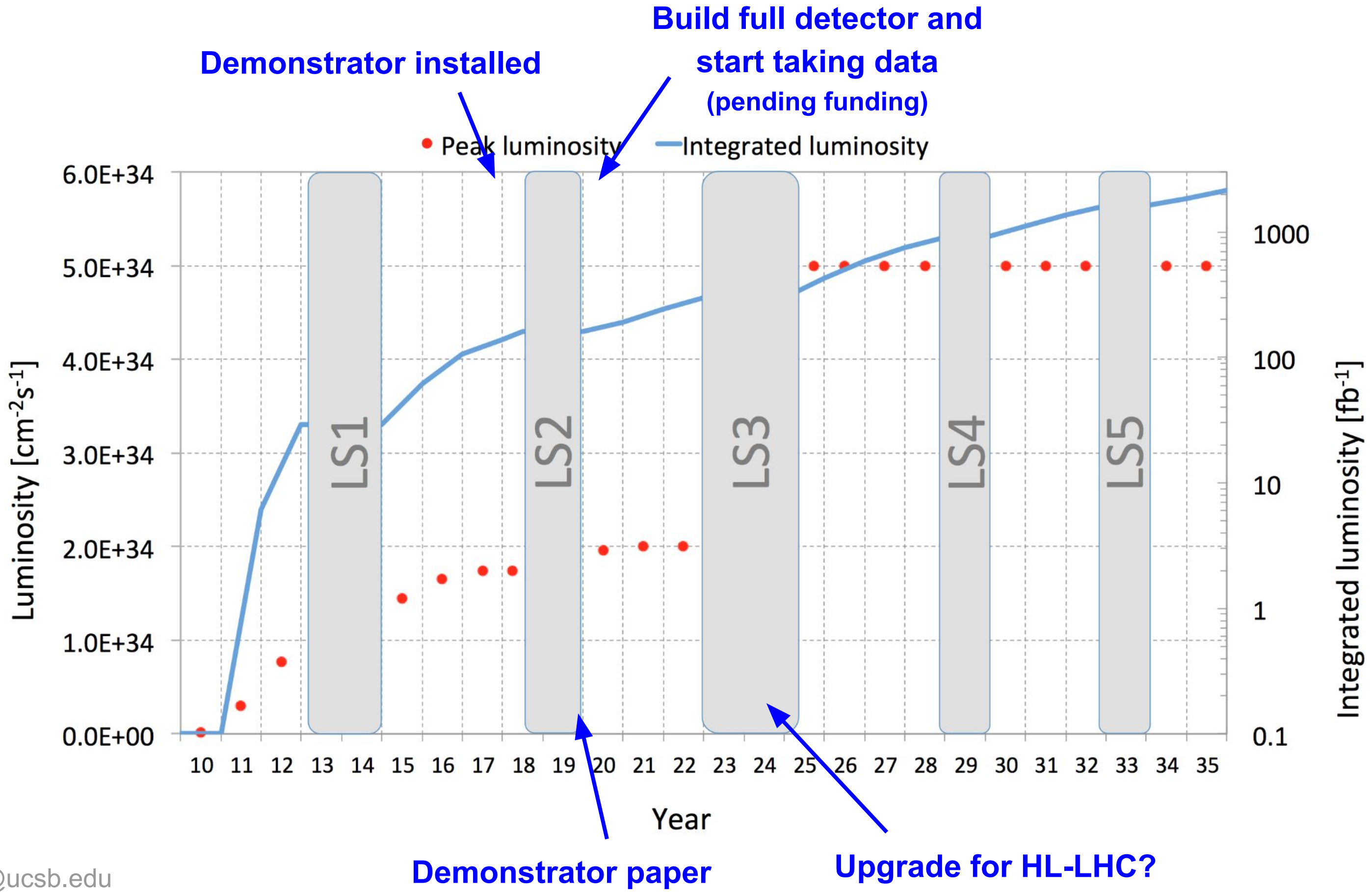
Timeline



Build full detector and
start taking data
(pending funding)
Demonstrator installed
Peak luminosity
Integrated luminosity
6.0E+34
5.0E+34
4.0E+34
3.0E+34
2.0E+34
1.0E+34
0.0E+00
Luminosity [cm-2s-1]
1000
100
10
1
0.1
Integrated luminosity [fb-1]
LS1
LS2
LS3
LS4
LS5
10 11 12 13 14 15 16 17 18 19 20 21 22 23 24 25 26 27 28 29 30 31 32 33 34 35
Year
Demonstrator paper
Upgrade for HL-LHC?

Conclusions

- **milliQan** is a new (relatively simple) experiment designed to achieve the first sensitivity to charges of $O(10^{-3})$ in the GeV mass range
- Have designed, constructed, and operated a small-scale demonstrator to study backgrounds, prove feasibility for a larger detector, and even provide some sensitivity to unexcluded phase space
- Plan a publication with 2018 demonstrator data soon
- Full, four-layer detector design is finalized
- Ready for construction, but we await funding for the full experiment

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milliQan collaboration

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M. Carrigan

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A. Haas,
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M. Swiatlowski

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A. Ball, A. De Roeck,
M. Gastal, R. Loos

M. Ezzeldine,
H. Zaraket

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J. Brooke,
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Backup

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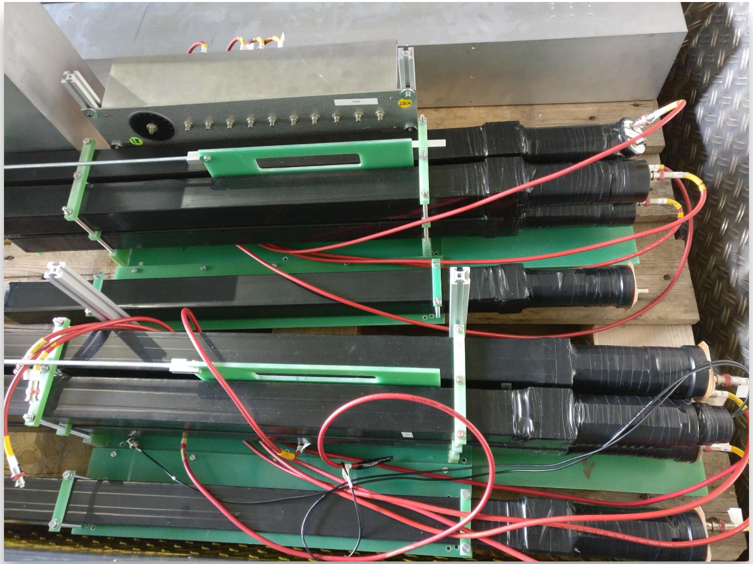
Module construction

Bars wrapped in layers of reflective and light blocking materials
(including tyvek, tinfoil, electrical tape)



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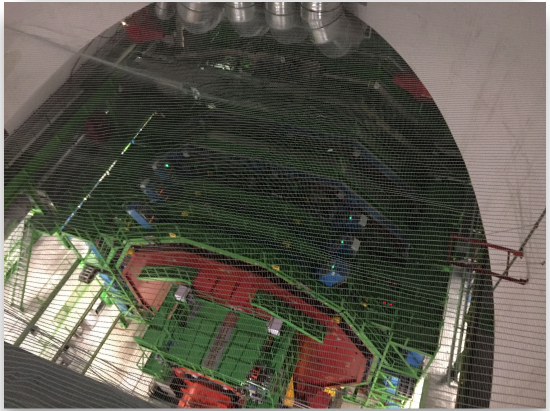
Module construction



Modules assembled on the surface and then lowered to gallery

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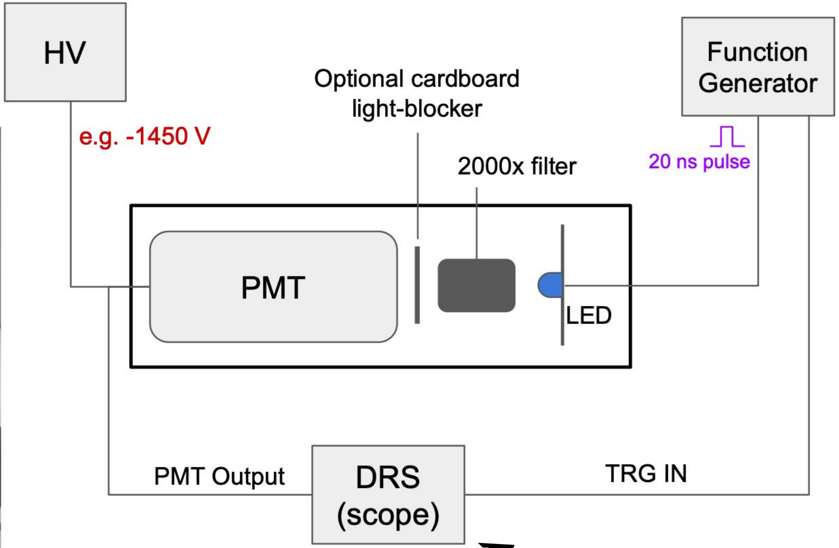
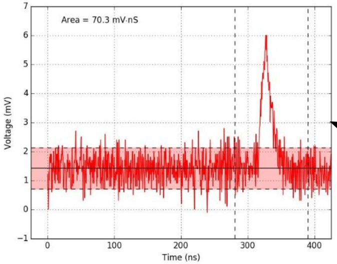
PMT SPE calibration using LEDs



Send simultaneous LED pulse and trigger



Digitise and record waveforms

Measure pulse area using integral of window

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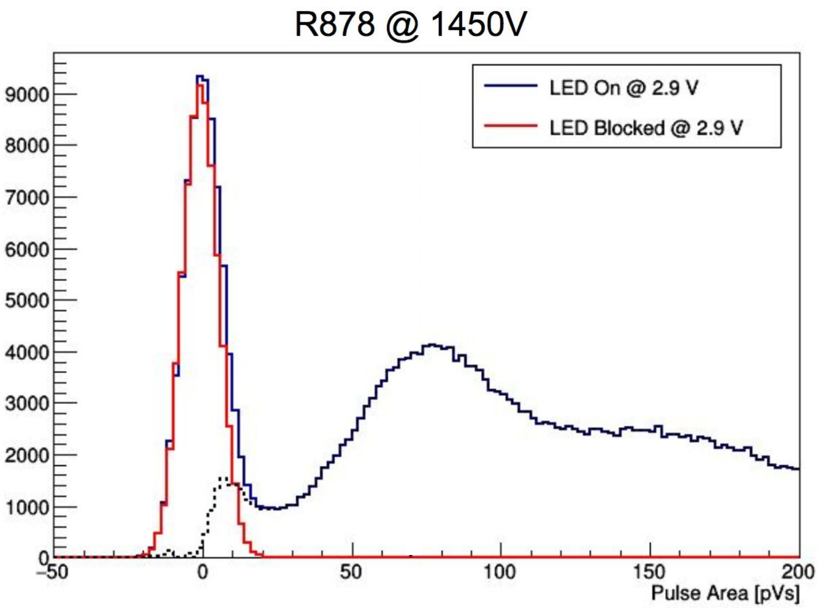
PMT SPE calibration using LEDs

Measure pulse area spectrum with a low intensity LED (so mean NPE < 1)

Measure 0-PE distribution with “LED blocked” configuration

Scale left edges and subtract off 0-PE component

Can get mean/StDev of SPE area distribution by assuming poisson distribution



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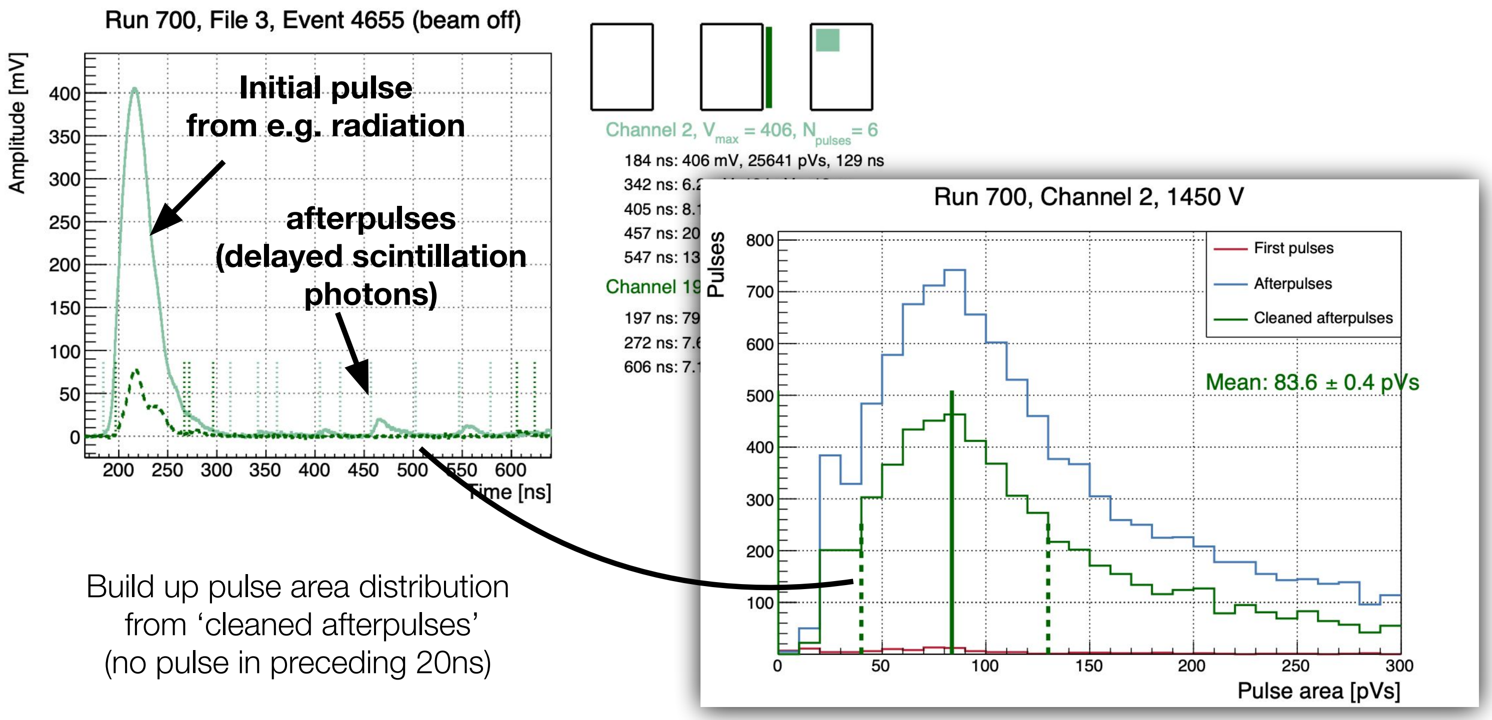
Calibration from delayed scintillation pulses



Build up pulse area distribution
from 'cleaned afterpulses'
(no pulse in preceding 20ns)

e.g. R878 PMT

Mean within half-width-max
gives SPE pulse area

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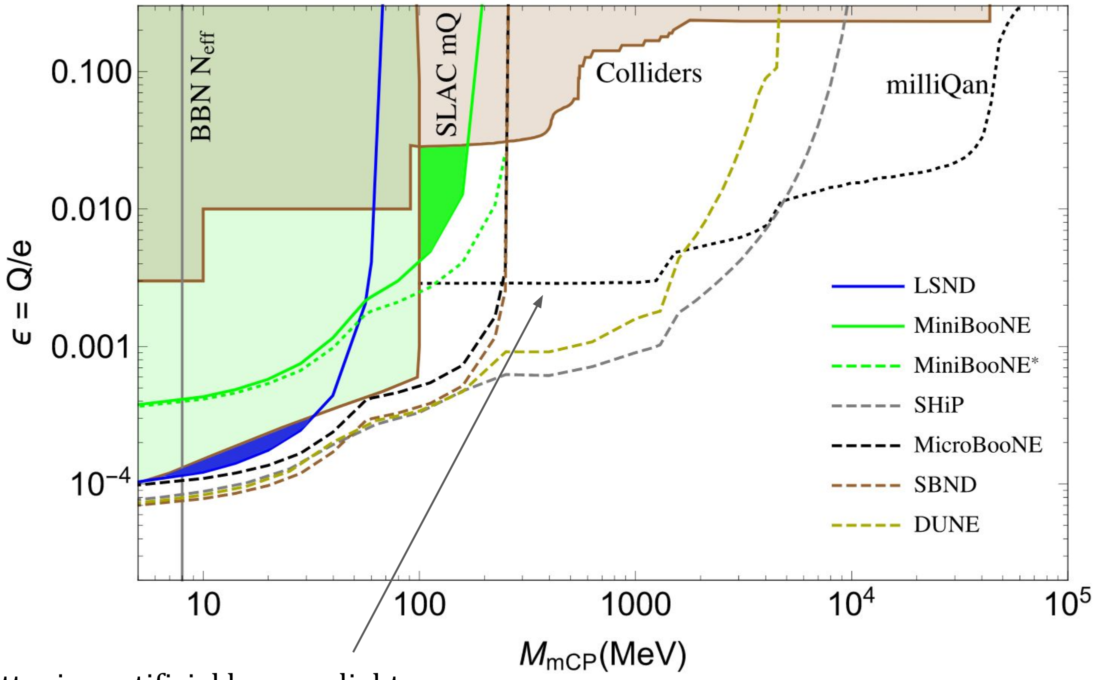
Limit comparisons (from pheno paper)



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arxiv1806.03310