

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

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on behalf of the milliQan collaboration

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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

Why milli-charged particles?

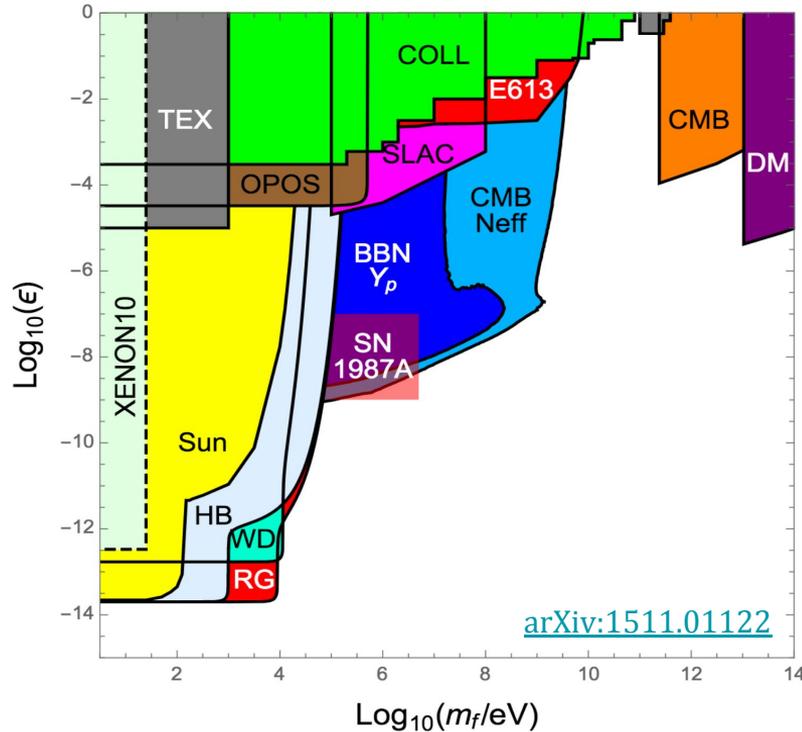
- Dark sector can be introduced into the SM with the addition of a “dark photon” A' , that couples to a massive “dark fermion” ψ' with strength e'

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

massless “dark photon”
mixing term ($\kappa \ll 1$)

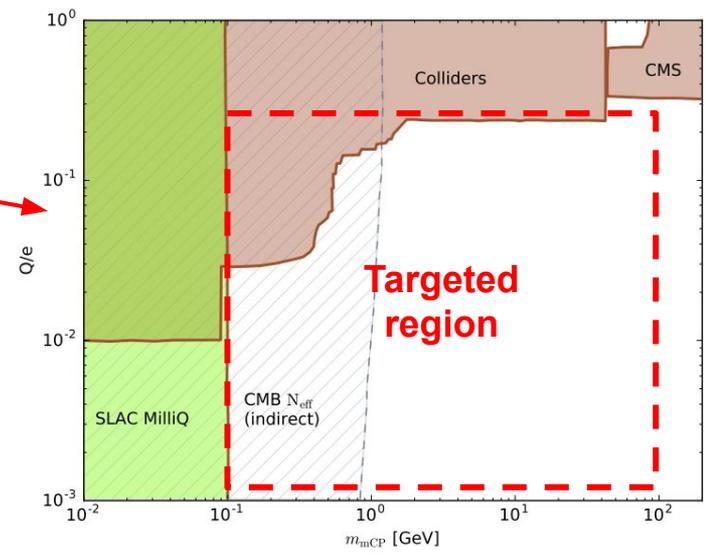
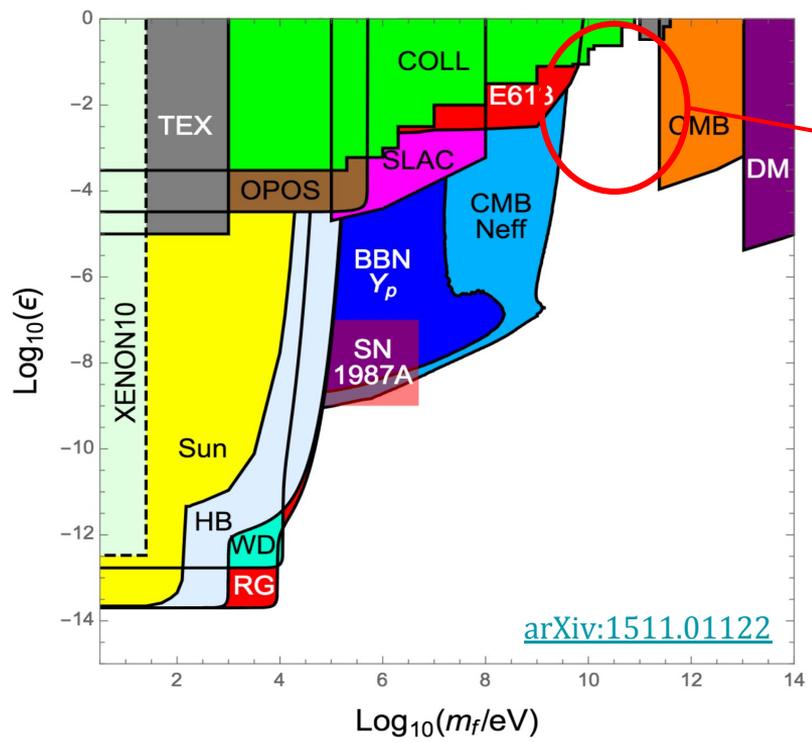
- Small mixing term between A' and weak hypercharge B provides a **link to SM**
- Standard gauge transformation $A'_\mu \rightarrow A'_\mu + \kappa B_\mu$ eliminates mixing term, and introduces a coupling between ψ' and B via $\bar{\psi}'\kappa e'\gamma^\mu B_\mu\psi'$
- So ψ' couples to SM photon with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

Status of searches



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

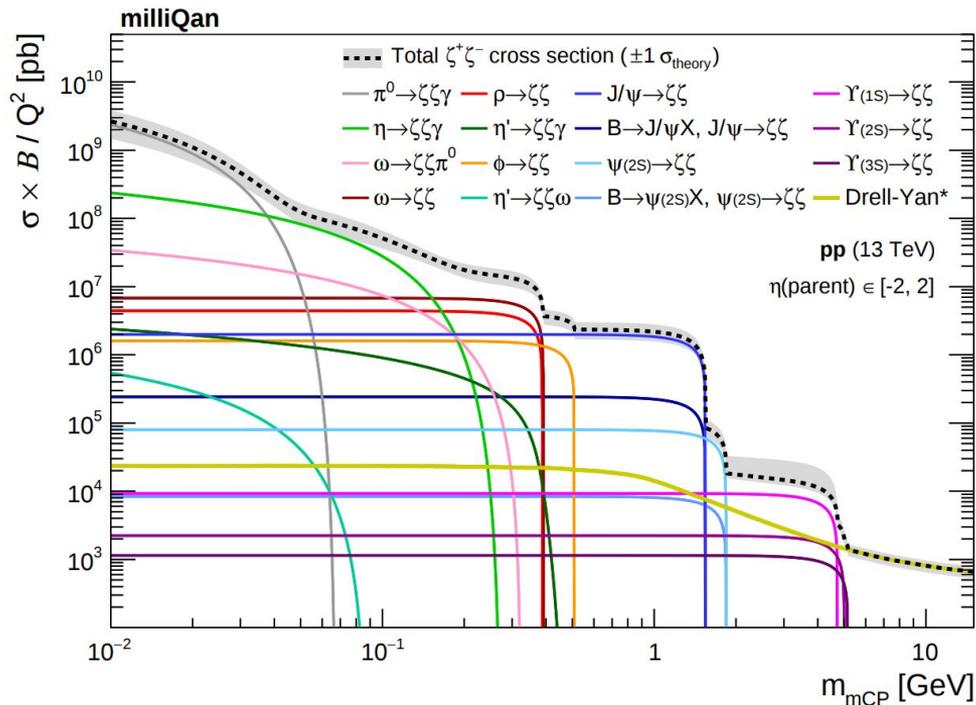
Status of searches



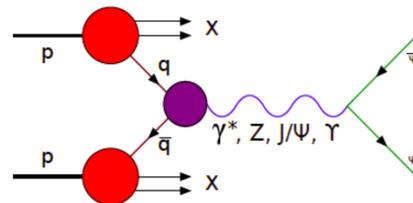
Gap at high mass and charge between 10^{-3} and $10^{-1} e$

Can target with a dedicated experiment at the LHC!

mCP production at the LHC

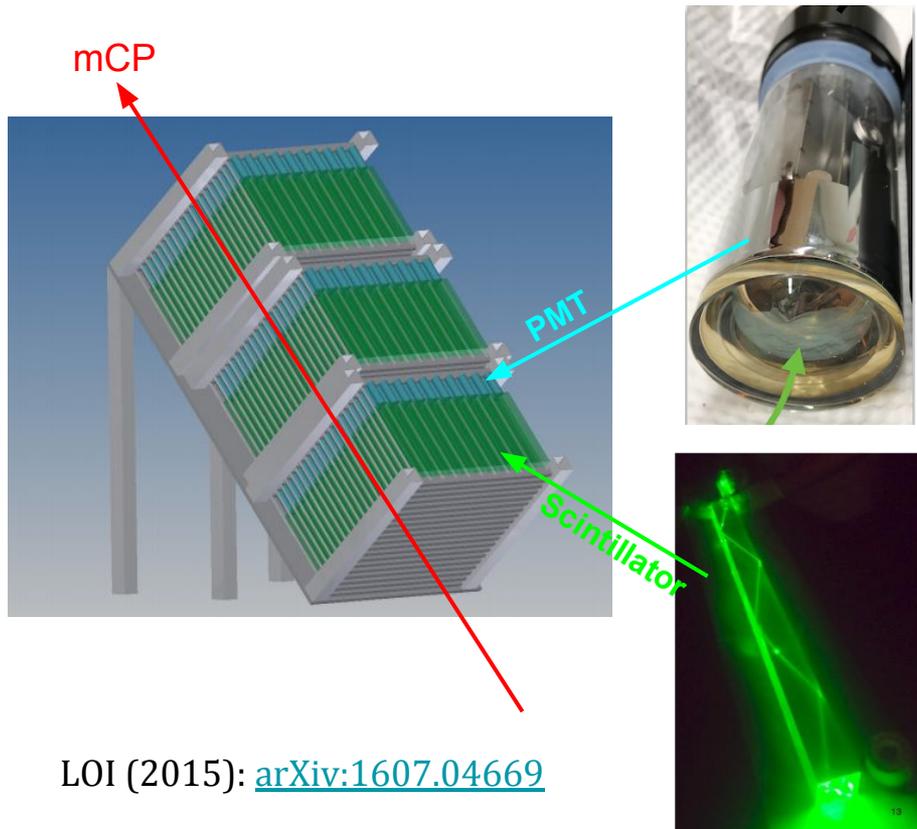


- Any process that produces an e^+e^- pair via a virtual photon can also produce an mCP pair
- Branching ratios can be computed as functions of mass/charge (scales as Q^2)
- Low masses dominated by QCD production of $\pi^0, \eta, \rho, \omega, \phi$
- Masses near 1 GeV dominated by J/ψ decays, then Y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



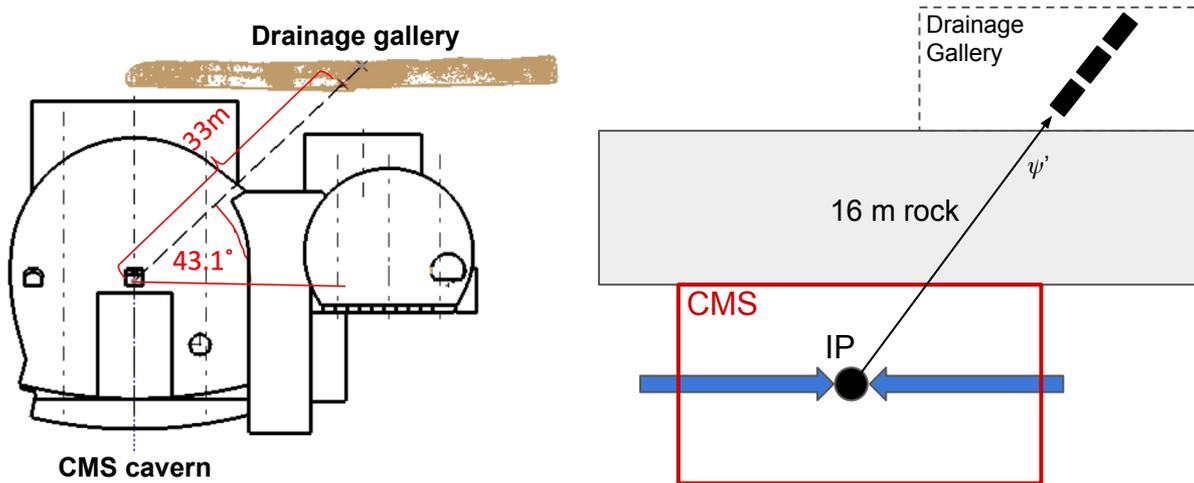
milliQan concept

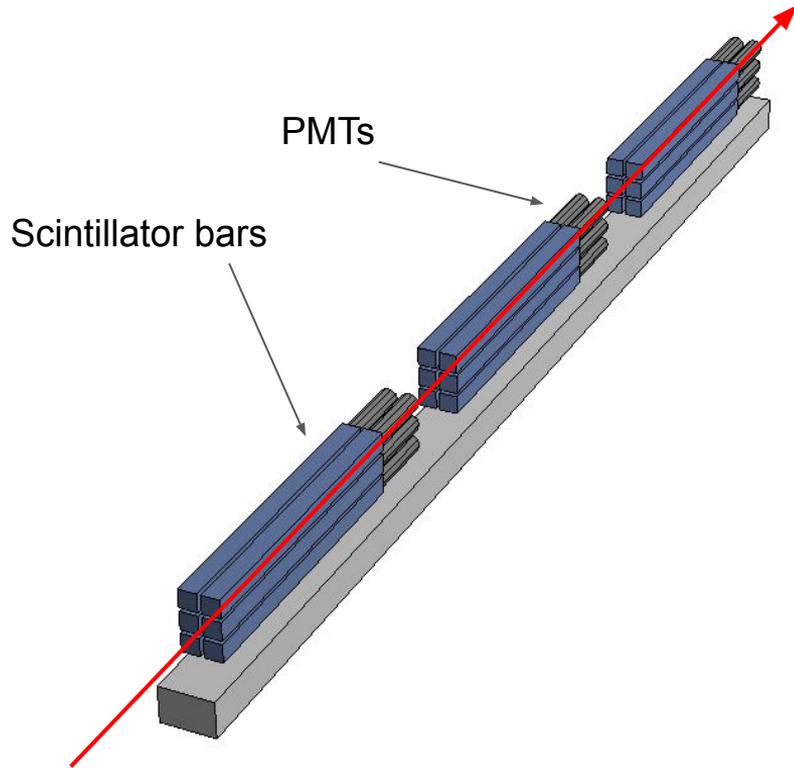
- Array of **scintillator bars** coupled to **PMTs** that can detect individual photoelectrons produced by through-going milli-charged particles
- Key concept is the **three-layer design**, requiring simultaneous hits in all three layers – drastically cuts down on backgrounds
- Signal would appear as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



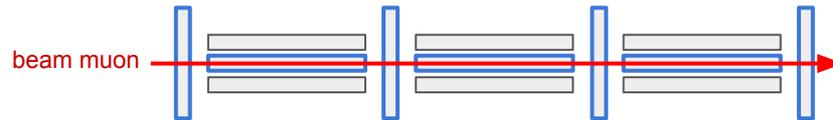
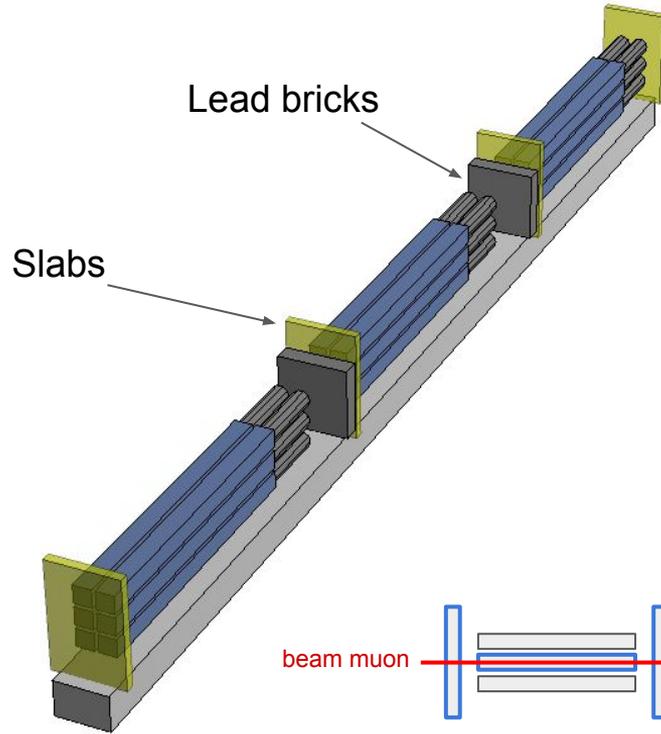
milliQan location

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

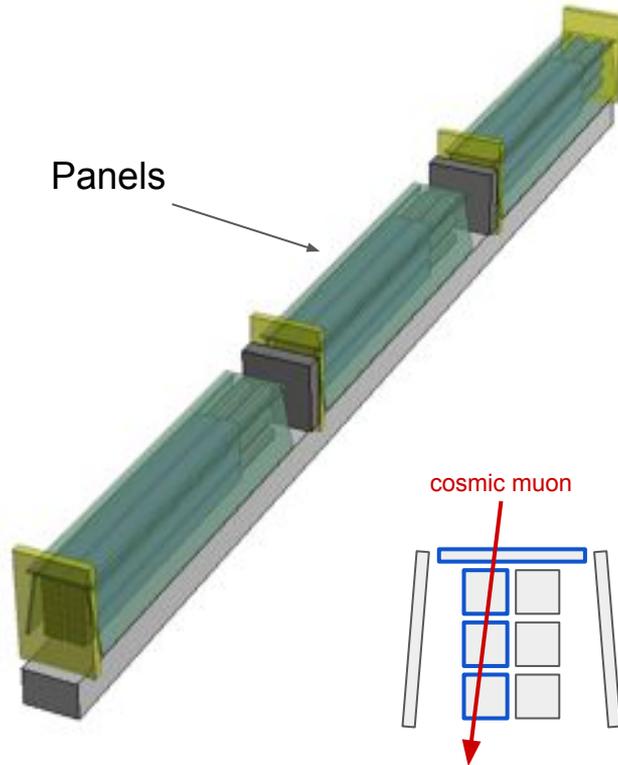




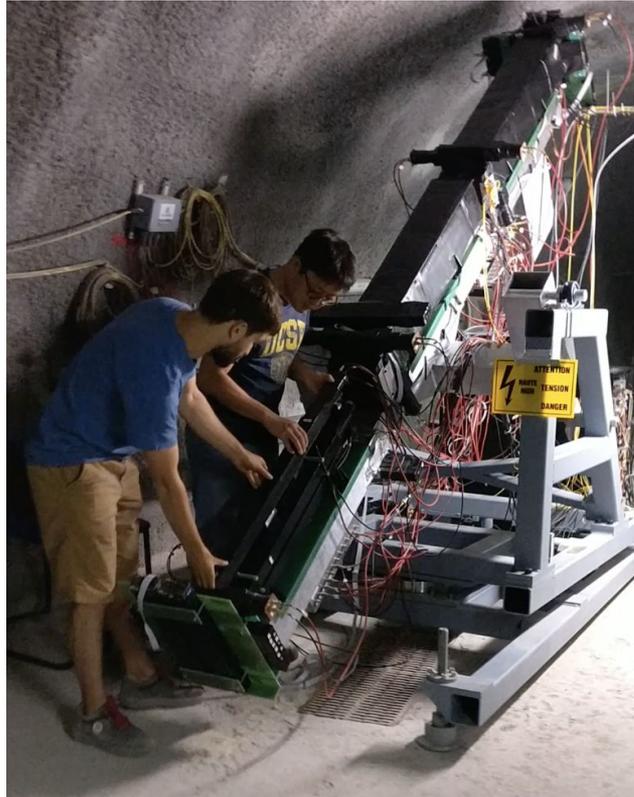
- In 2017/18, a smaller **demonstrator** was installed as a proof-of-concept and to study backgrounds
- 3 layers of 2x3 scintillator bar arrays (~1% of full milliQan)



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- Scintillator **slabs** to tag through-going particles and **lead bricks** to shield radiation



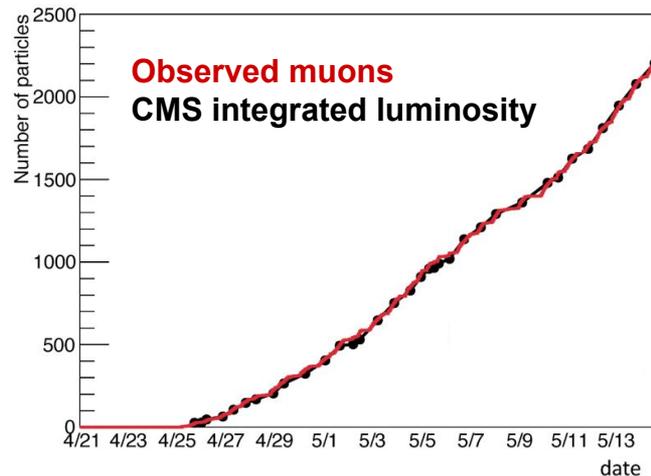
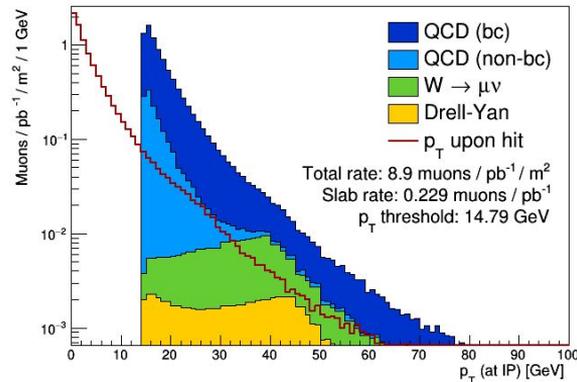
- In 2017/18, a smaller **demonstrator** was installed as a proof-of-concept and to study backgrounds
- 3 layers of 2x3 scintillator bar arrays (~1% of full milliQan)
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- 3 scintillator **panels** covering each layer to tag cosmic muons



- Placed on a custom-built aluminum stand, aligned by CERN team to point at interaction point
- Successfully collected $\sim 37 \text{ fb}^{-1}/2000\text{h}$ 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

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 $0.25 \pm 0.08 / \text{pb}^{-1}$ (primary uncertainties from the B-hadron cross section and amount of material between IP and detector)
- Observed rate in **data** is $0.18 / \text{pb}^{-1}$
- **Angular distribution** of muons is also validated

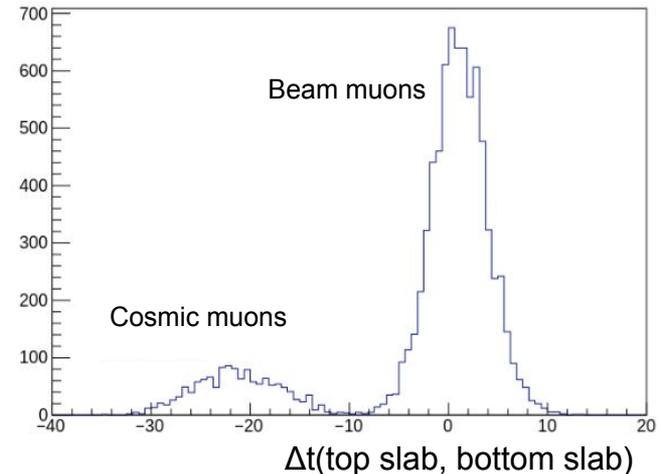
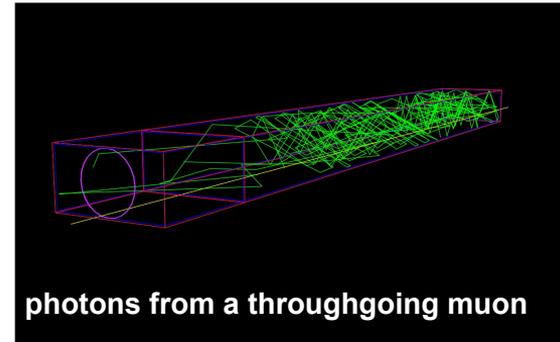


- **Charge calibration**

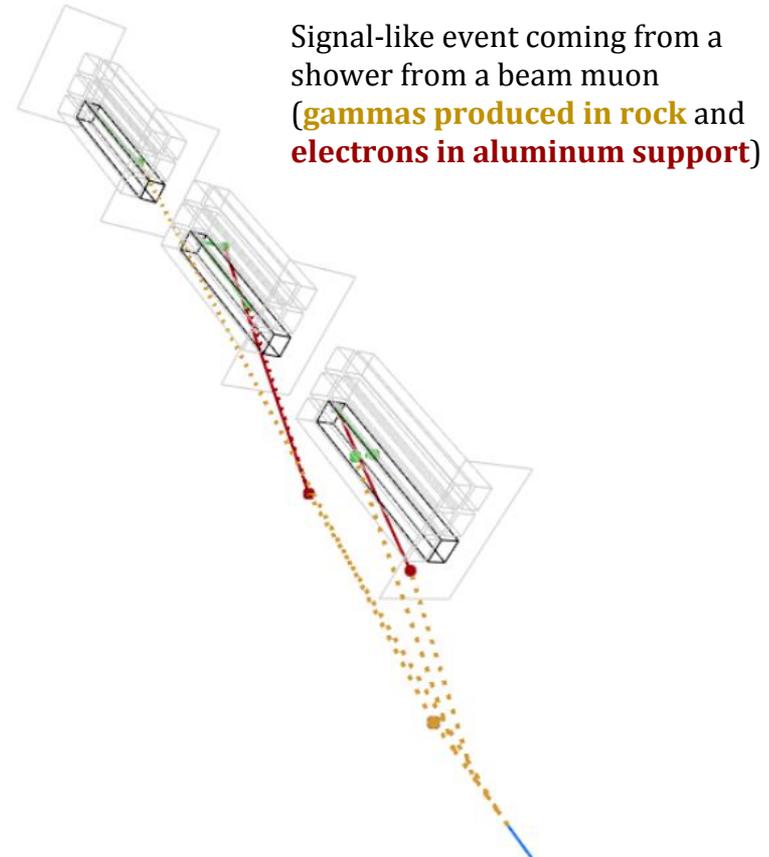
- Important to obtain a per-channel measurement of the number of observed PE per incident particle charge/distance traversed
- Individual PMT responses calibrated using afterpulses (checked with LED bench tests)
- Scintillators calibrated with vertical cosmics

- **Time calibration**

- Must account for geometry, cable length, PMT rise time
- Calibrated using beam/cosmic muons
- Time resolution of **4 ns** achieved

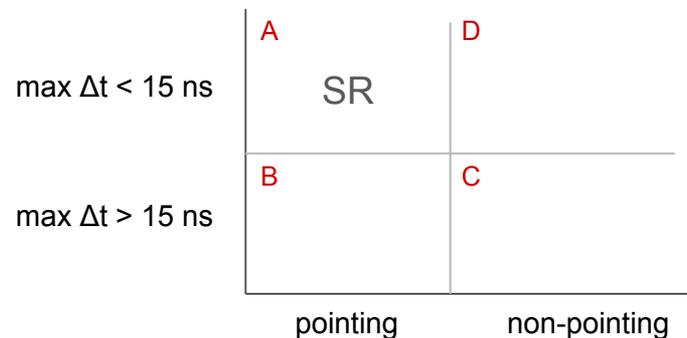
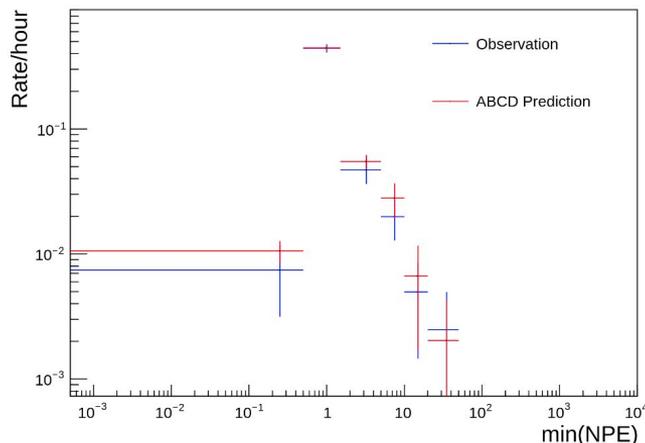


- Backgrounds come from 3 in-time hits from either the same process or a mixture of processes
 - PMT dark rate
 - Afterpulses
 - Radiation
 - Showers from beam/cosmic muons
- Important lesson from demonstrator: **PMT dark rate is a subdominant background source**
- Suggests that further background suppression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



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)



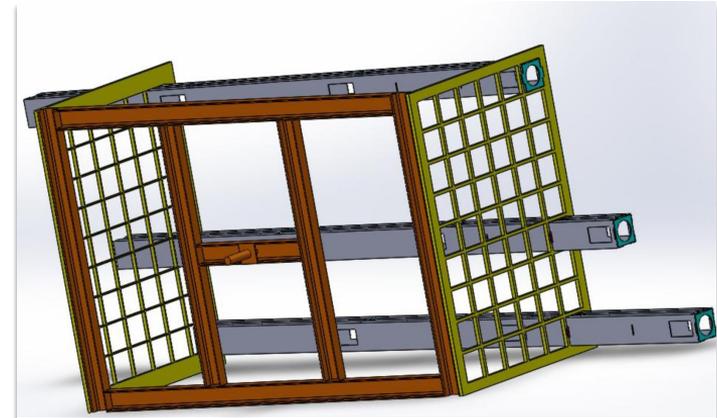
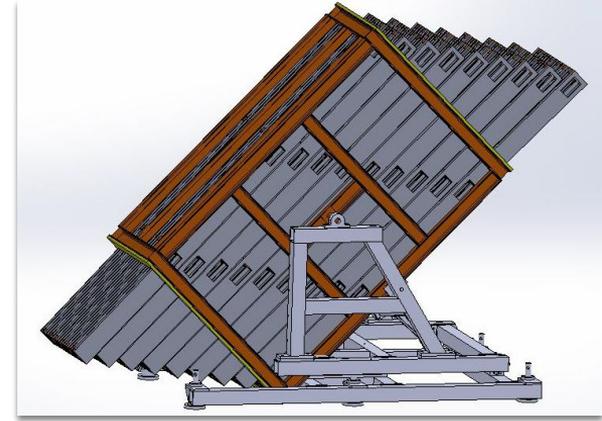
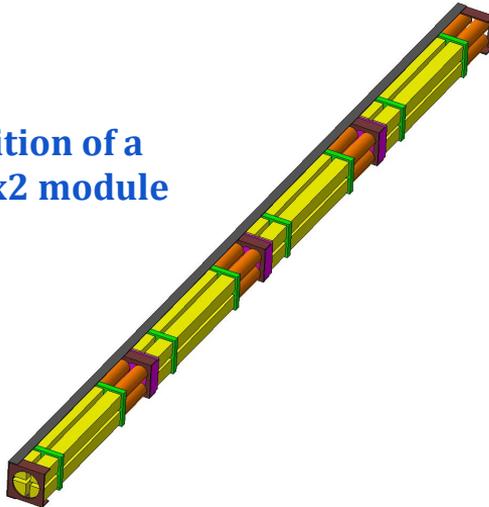
$$N_A = \frac{N_B}{N_C} N_D$$

- Individually generate mCP decays from all relevant production processes (light mesons, J/ψ , ψ , ψ' , $\psi(2S)$, $\psi(3770)$, $\psi(4040)$, $\psi(4180)$, $\psi(4230)$, $\psi(4360)$, $\psi(4440)$, $\psi(4660)$, $\psi(5040)$, $\psi(5774)$, $\psi(5972)$, $\psi(6040)$, $\psi(6690)$, $\psi(7234)$, $\psi(7430)$, $\psi(7684)$, $\psi(8438)$, $\psi(8956)$, $\psi(9460)$, $\psi(9593)$, $\psi(9750)$, $\psi(9792)$, $\psi(9843)$, $\psi(10023)$, $\psi(10393)$, $\psi(10424)$, $\psi(10578)$, $\psi(10703)$, $\psi(10940)$, $\psi(11020)$, $\psi(11231)$, $\psi(11358)$, $\psi(11494)$, $\psi(11654)$, $\psi(11811)$, $\psi(11974)$, $\psi(12138)$, $\psi(12303)$, $\psi(12460)$, $\psi(12617)$, $\psi(12774)$, $\psi(12931)$, $\psi(13088)$, $\psi(13245)$, $\psi(13402)$, $\psi(13559)$, $\psi(13716)$, $\psi(13873)$, $\psi(14030)$, $\psi(14187)$, $\psi(14344)$, $\psi(14501)$, $\psi(14658)$, $\psi(14815)$, $\psi(14972)$, $\psi(15129)$, $\psi(15286)$, $\psi(15443)$, $\psi(15600)$, $\psi(15757)$, $\psi(15914)$, 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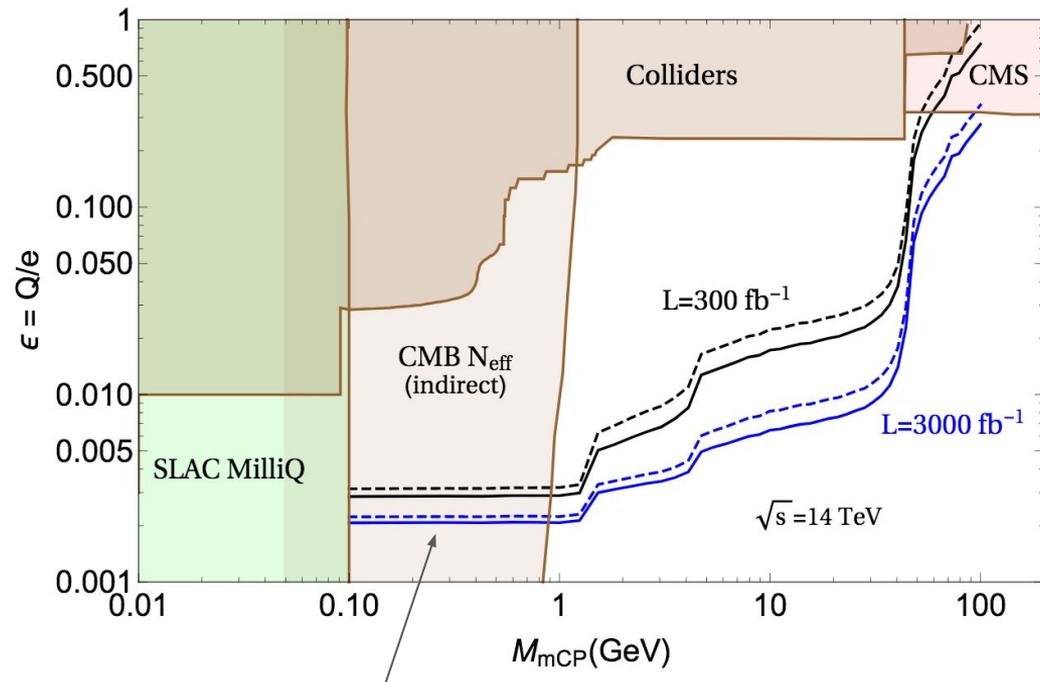
Plans for full detector

- 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



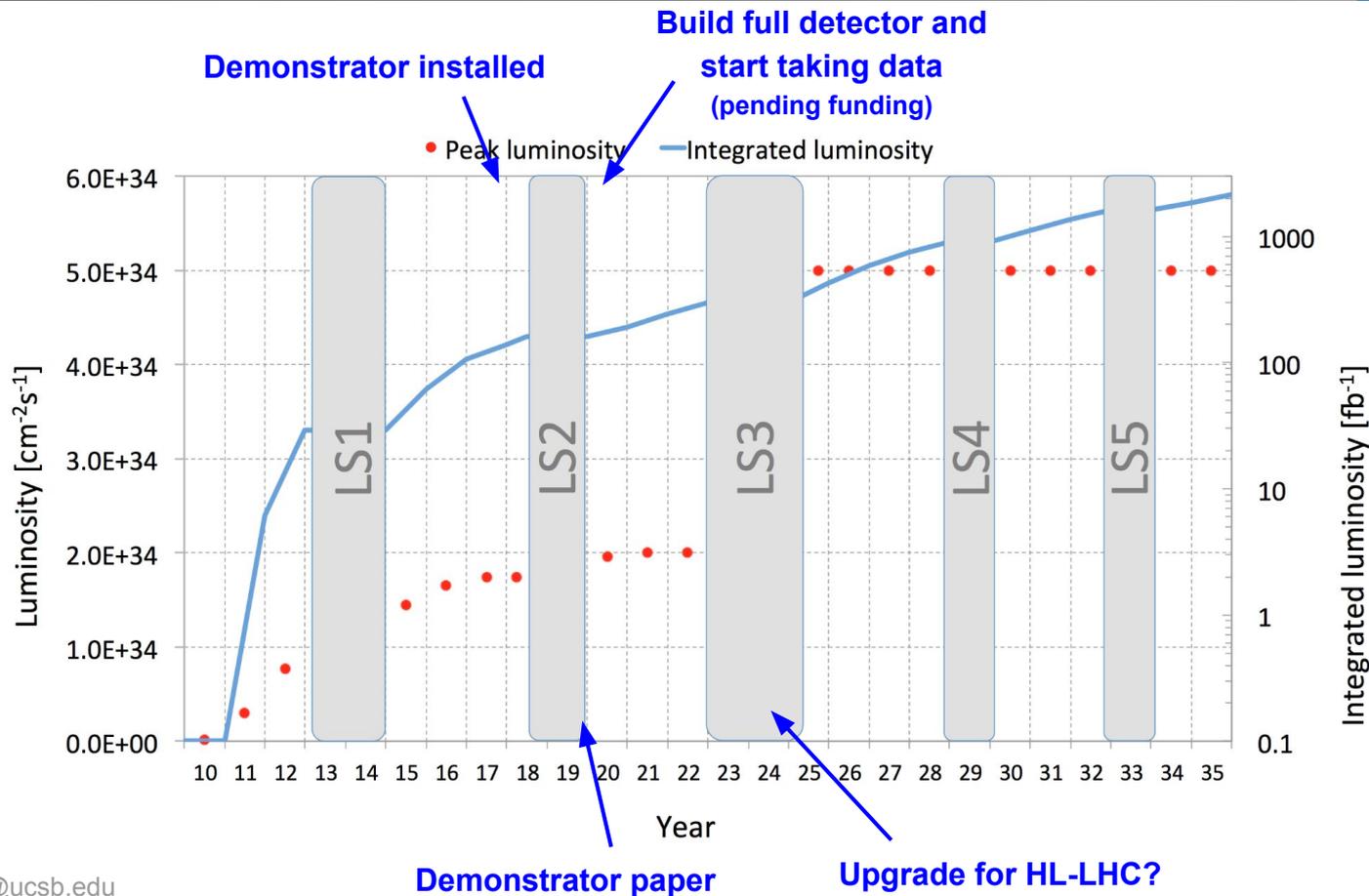
Full detector expected sensitivity



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

From 2015 LOI -- updated full detector projection coming soon

Timeline



- **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

milliQan collaboration



C. Hill,
B. Francis,
M. Carrigan



D. Stuart, C. Campagnari,
M. Citron, B. Marsh,
R. Schmitz, F. Setti, B. Odegard



A. Haas,
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D. Miller,
M. Swiatlowski



S. Lowette



R. Ulrich



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



M. Ezzeldine,
H. Zaraket



F. Golf



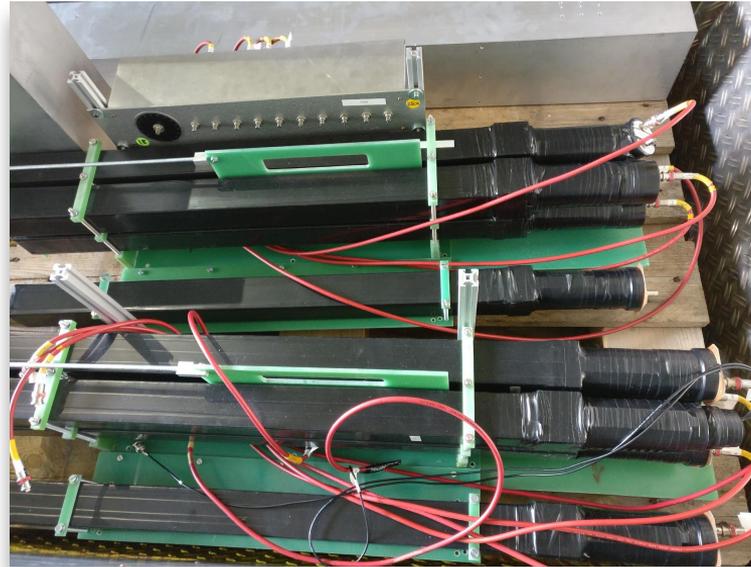
J. Brooke,
J. Goldstein

Backup

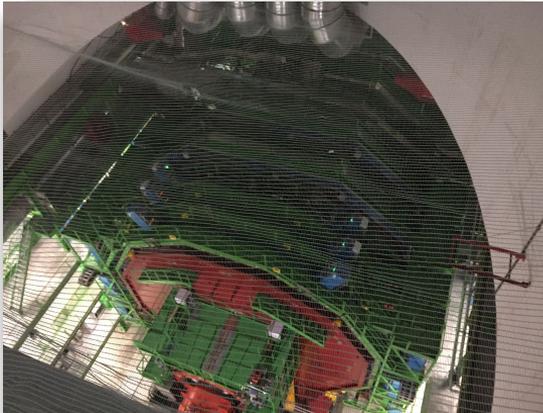
Module construction



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

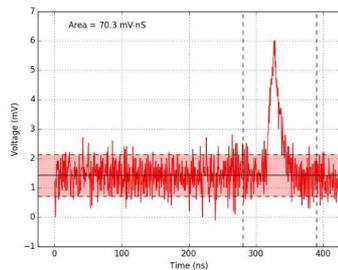
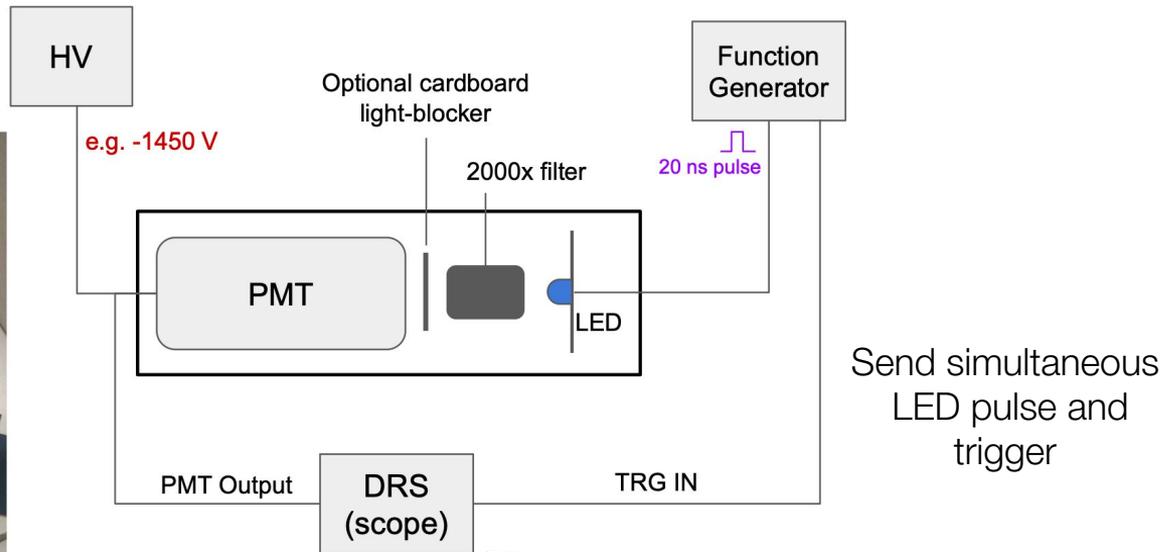


Module construction



Modules assembled on the surface and then lowered to gallery

PMT SPE calibration using LEDs



Digitise and record waveforms

Measure pulse area using integral of window

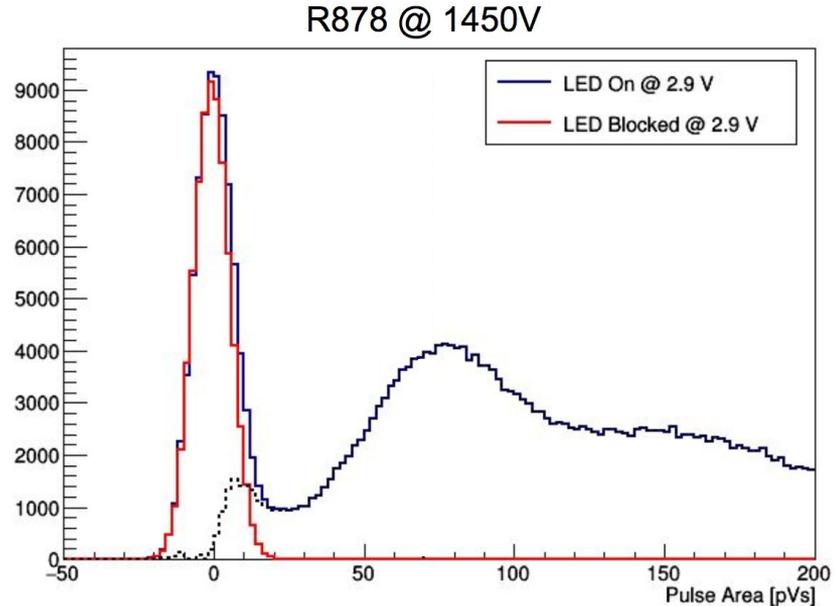
PMT SPE calibration using LEDs

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

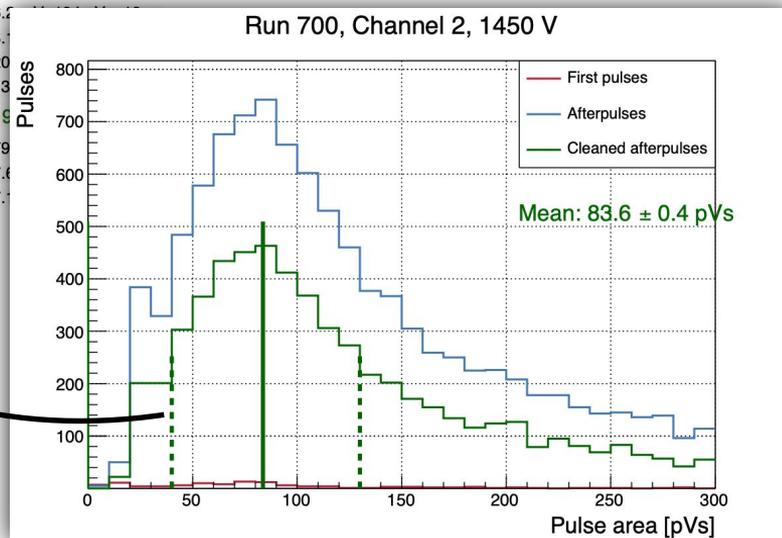
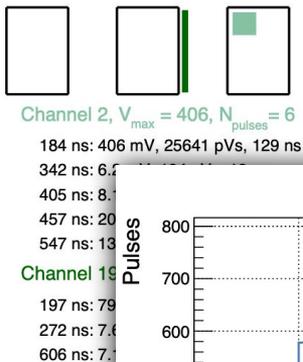
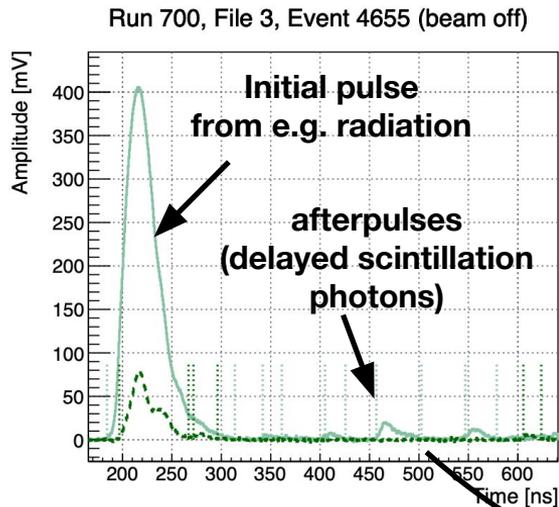
Measure 0-PE distribution with “LED blocked” configuration

Scale left edges and subtract off 0-PE component

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



Calibration from delayed scintillation pulses

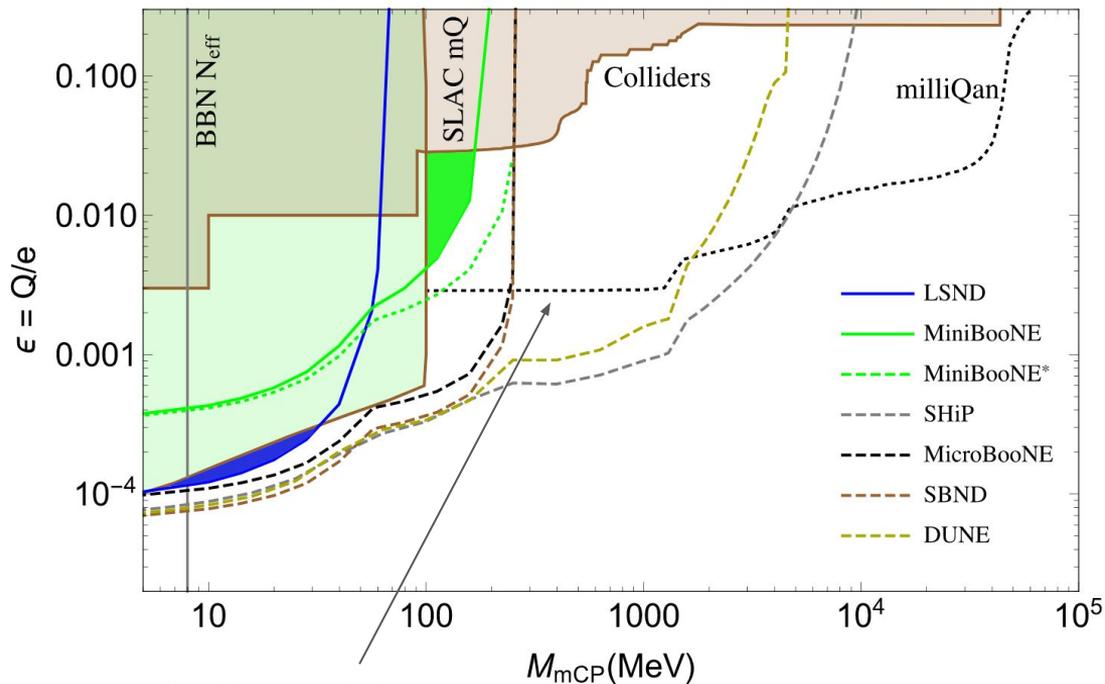


Build up pulse area distribution from 'cleaned afterpulses' (no pulse in preceding 20ns)

e.g. R878 PMT

Mean within half-width-max gives SPE pulse area

Limit comparisons (from pheno paper)



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

[arxiv1806.03310](https://arxiv.org/abs/1806.03310)