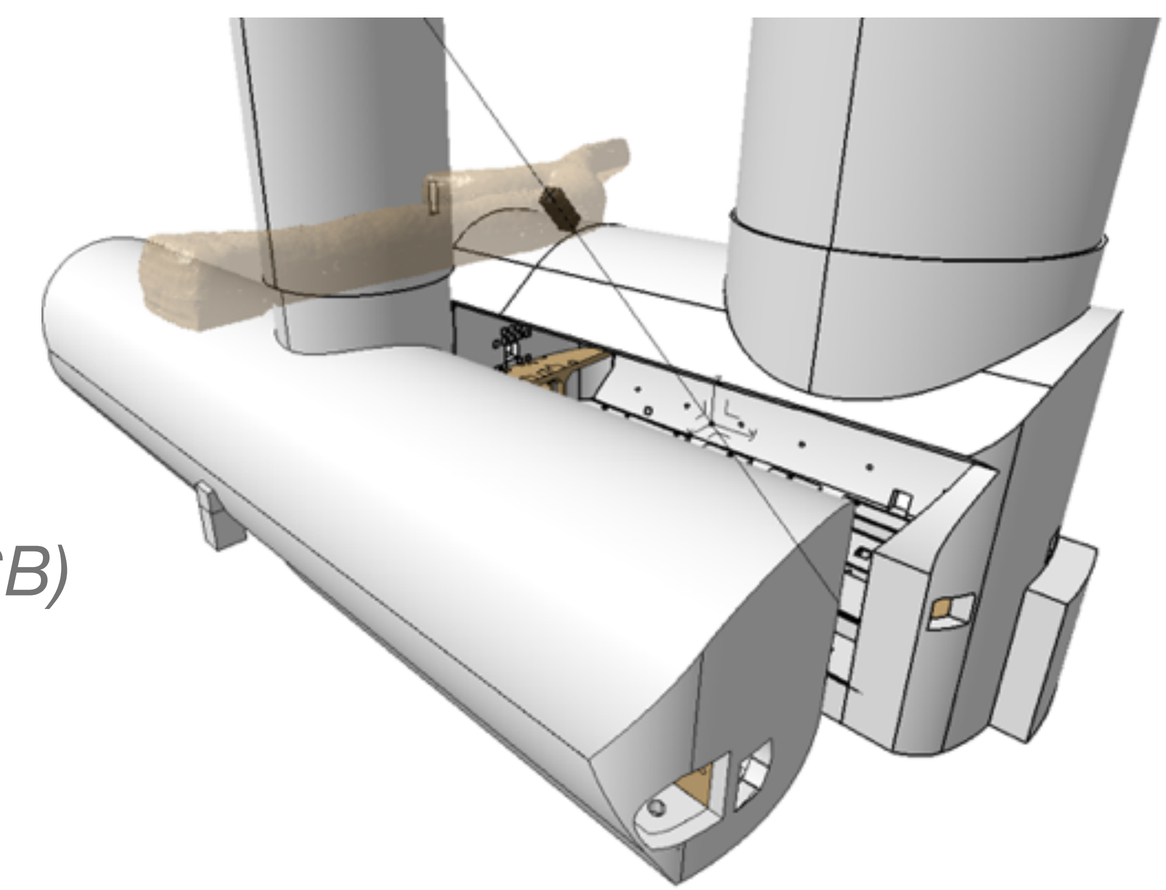
University of BRISTOL

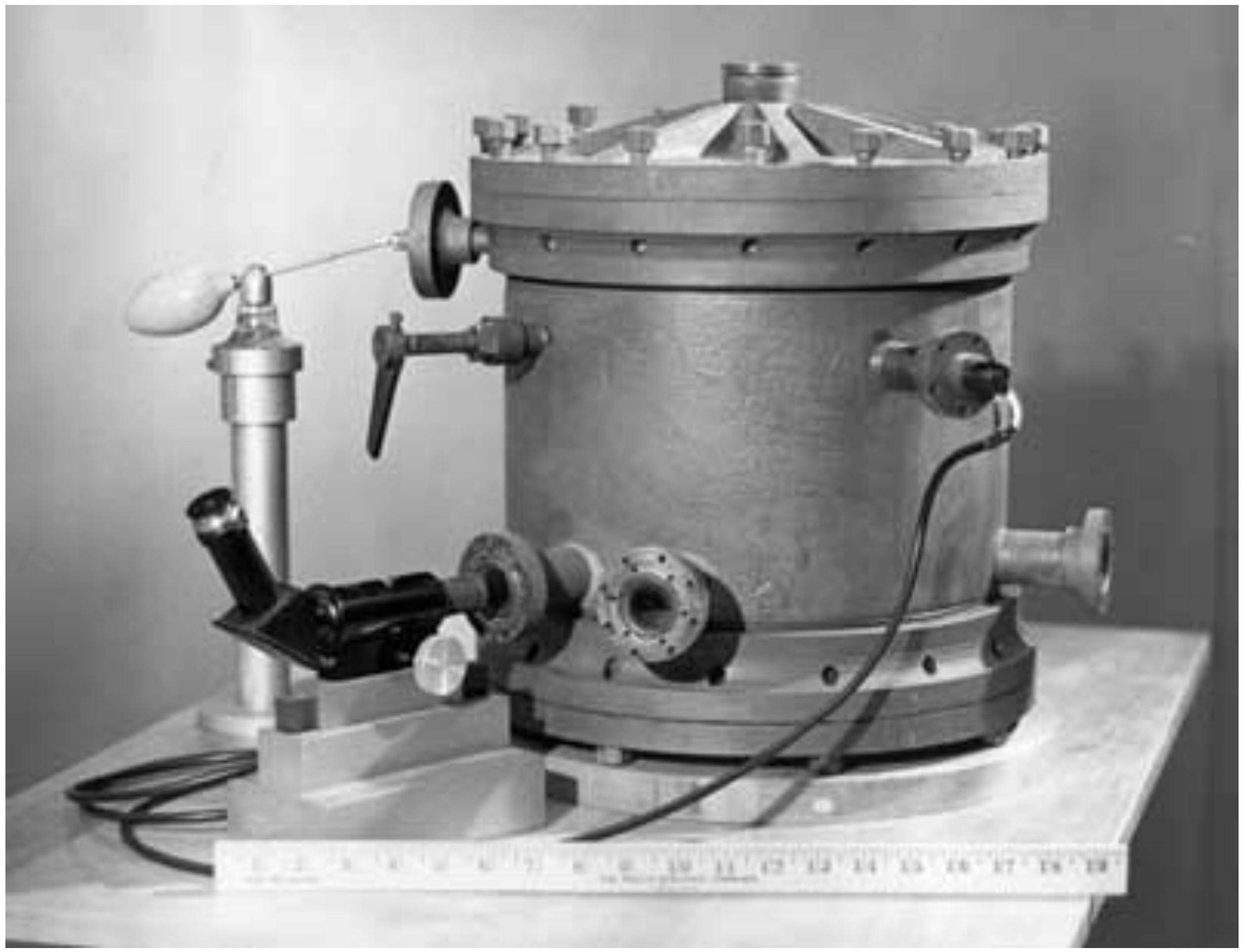
MilliQan - A Search for Milli-Charged Particles

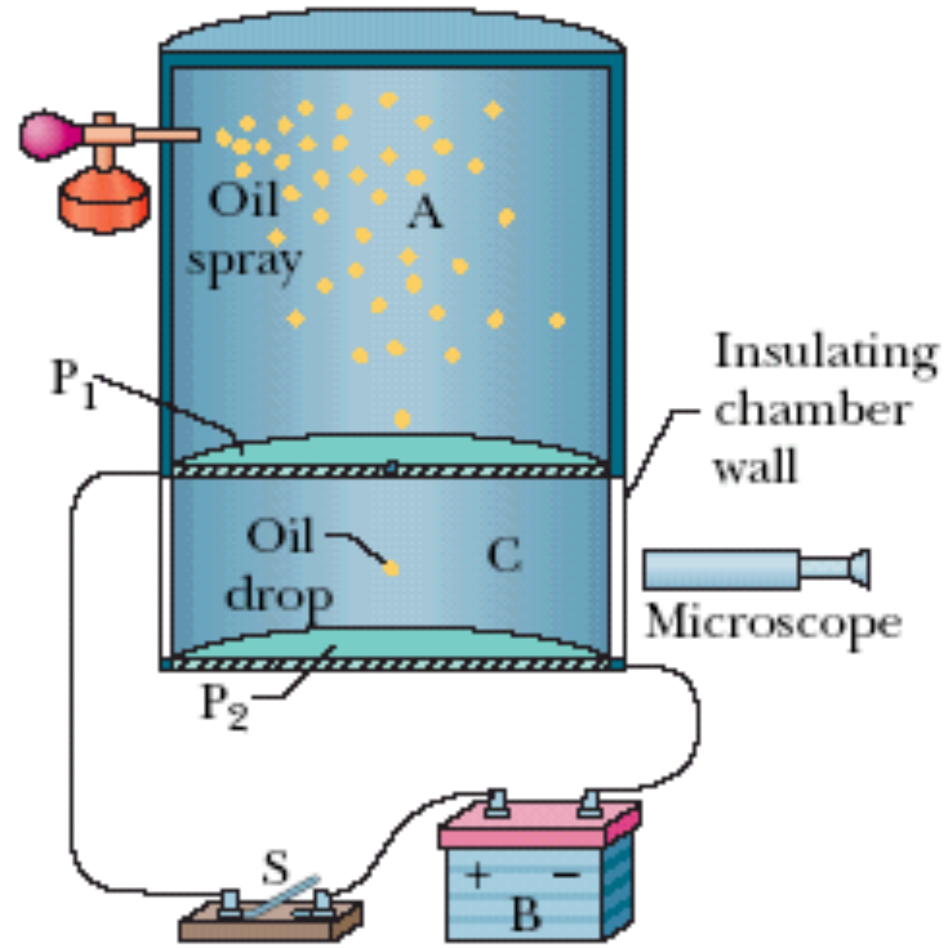
Jim Brooke



Thanks to C. Hill (OSU) and M. Citron (UCSB) for letting me borrow slides !

Millikan's Oil Drop Experiment





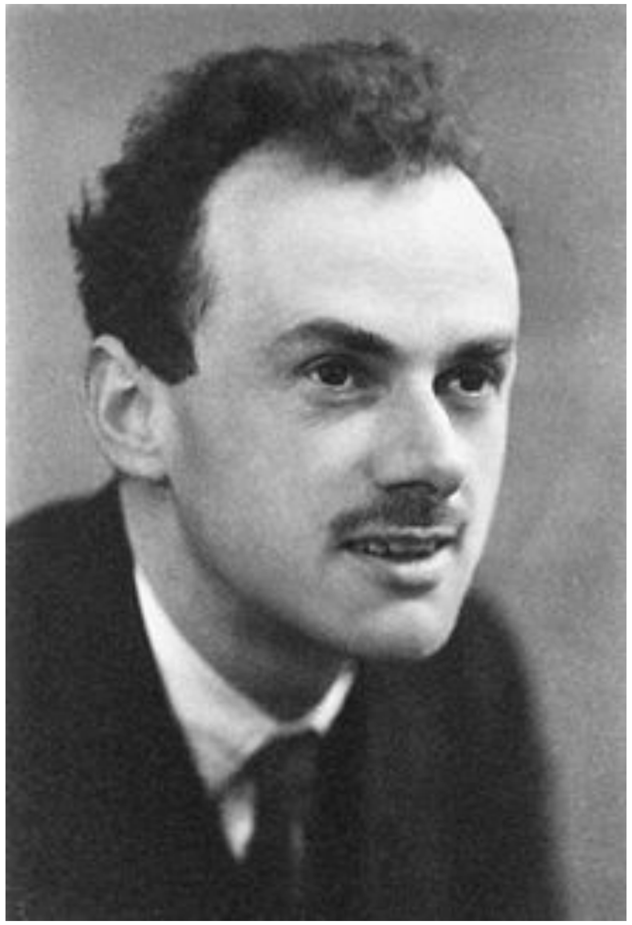
- Produce charged drops of oil in a chamber
- Drops falling at terminal velocity have $F_{drag} = F_{gravity}$, which allows the radius (and hence mass) to be determined
- Apply electric field, such that $F_{grav} = F_{elec} = qE$, to determine the charge on the drop…

Quantisation of Charge

- So electric charge is found in units of *e*
- Or, since the discovery of quarks, units of 1/3*e*
- Dirac hypothesised a system comprising an electric charge (*e*), and a magnetic monopole (q_m)
  - Since angular momentum must be quantised :

$$\frac{2eq_m}{\hbar c} \in \mathbb{Z}$$

- If there is a magnetic monopole, somewhere in the Universe, electric charge must be quantised…

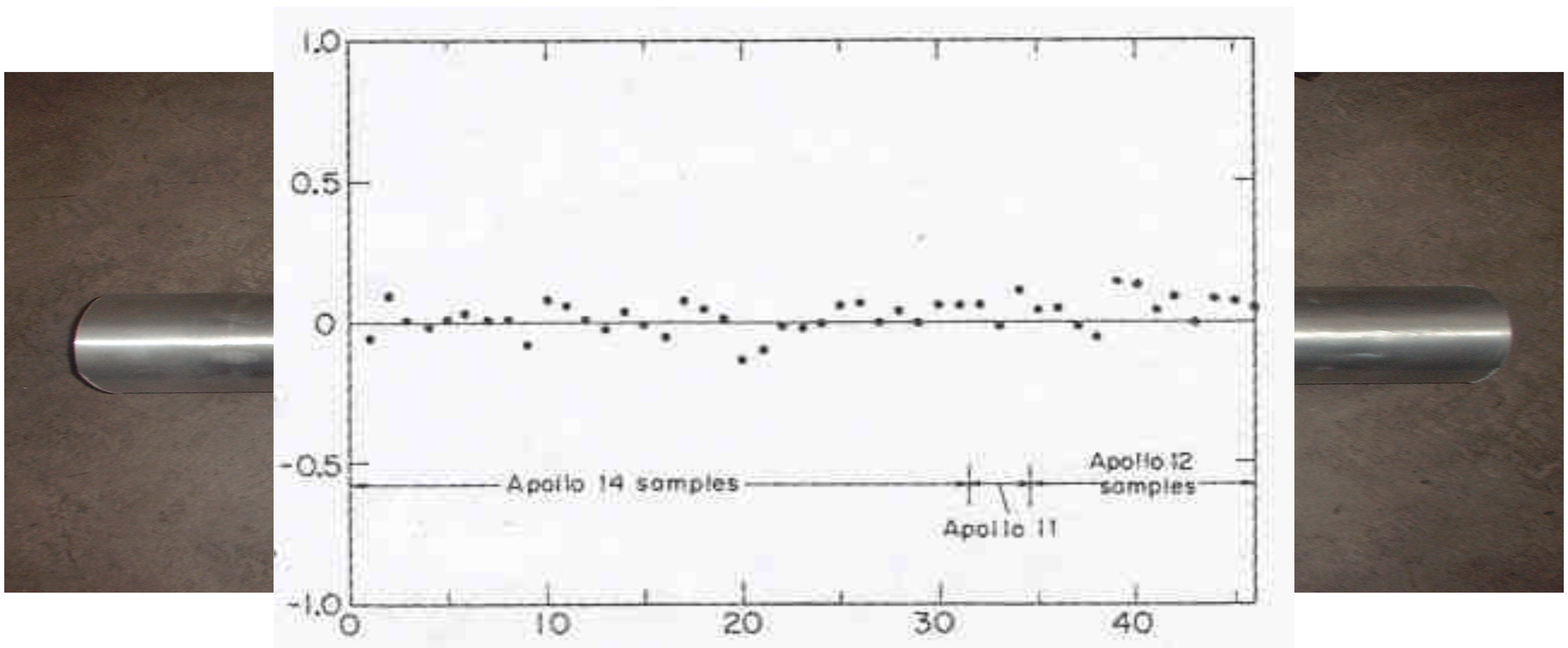


Monopole Searches

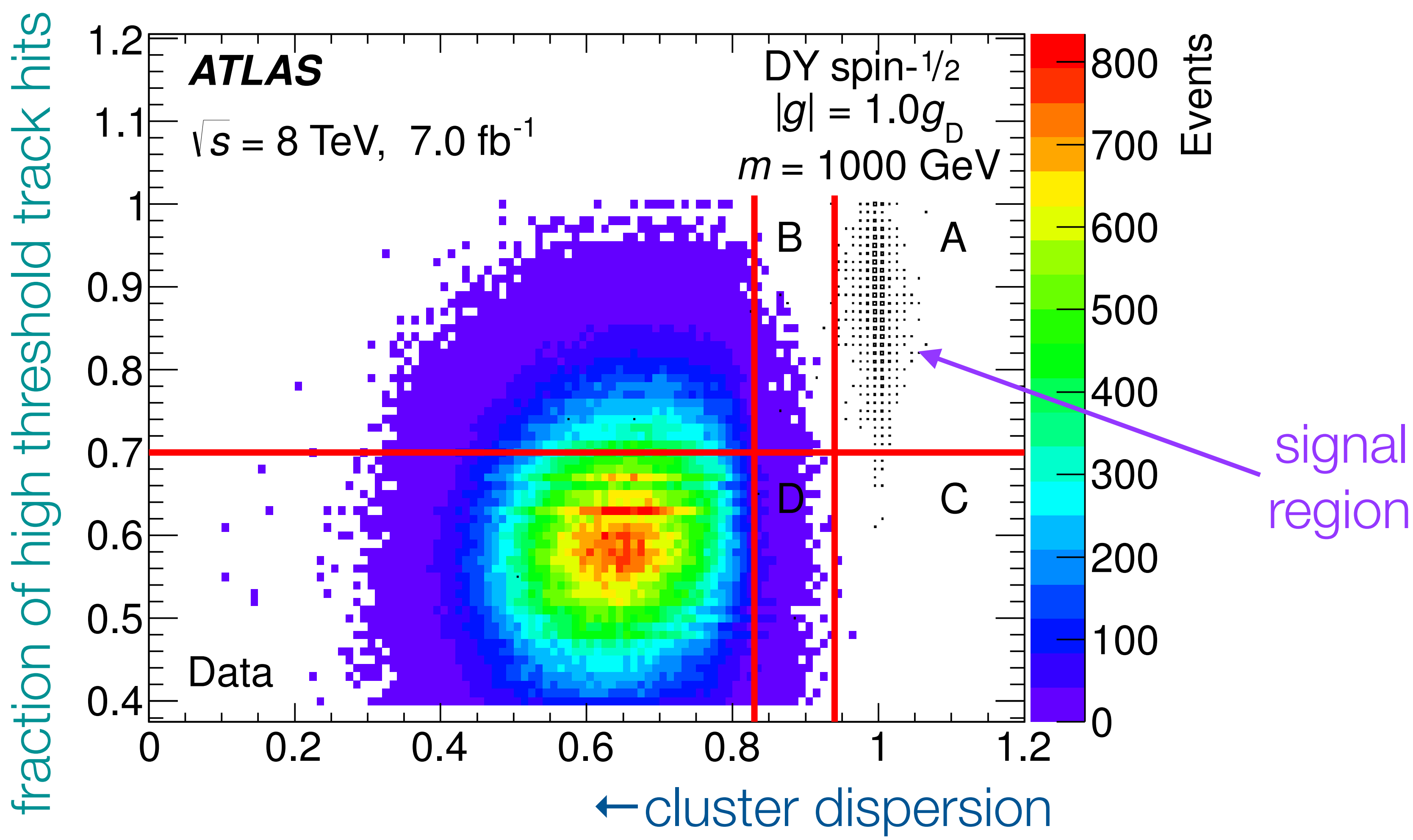
- It follows from $\frac{2eq_m}{\hbar c} \in \mathbb{Z}$ that the monopole magnetic charge is

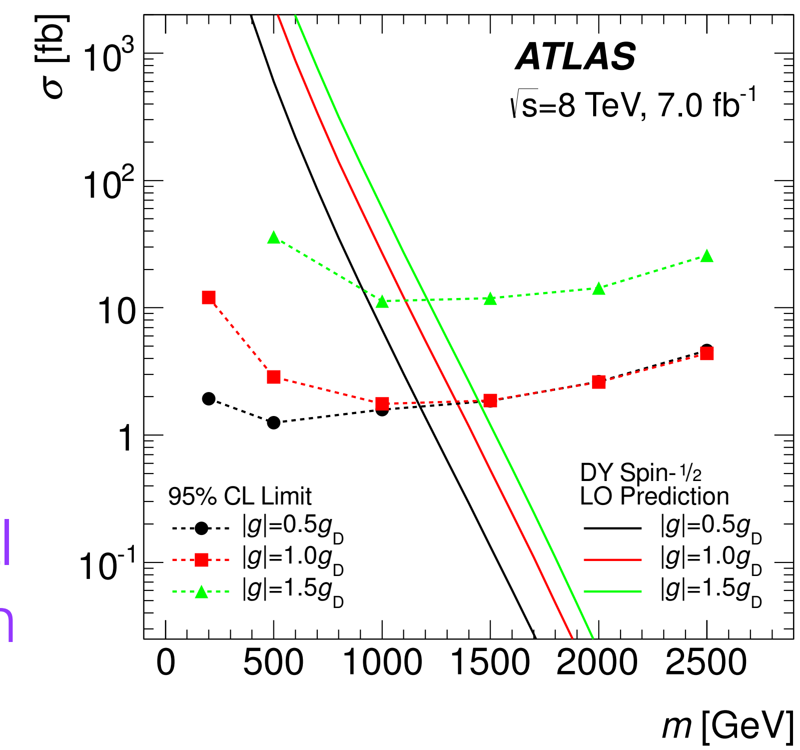
$$q_m = \frac{\hbar c}{2e} = \frac{e}{2\alpha} \sim 69e$$

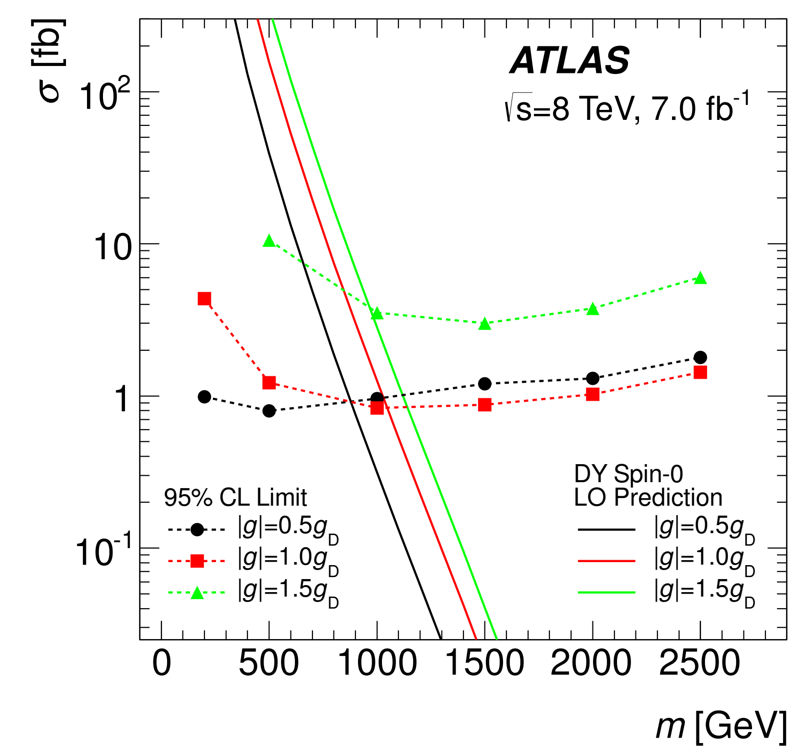
- In terms of ionisation energy loss, a monopole looks like an electrically charged particle with q ~ 69e
- Many searches for monopoles that have got stuck in things…



ATLAS Monopole Search





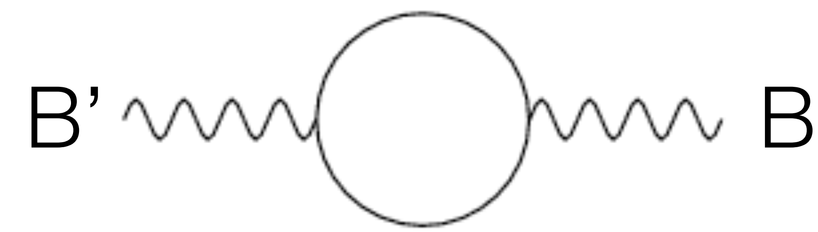


Search for tracks with high dE/dx, associated with narrow EM clusters

MilliCharged Particles

- Simple extension to the Standard Model is just to add a U(1) gauge symmetry

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



new 'dark' photon   kinetic mixing term

- Suppose we also have a new fermion, charged only under the new U(1)

- Interactions with electric charge can happen via kinetic mixing

Milli-charges

- Suppose we add a new fermion, charged only under the new U(1) :

$$\mathcal{L} = \mathcal{L}_{SM} - \frac{1}{4} B'^{\mu\nu} B'_{\mu\nu} + i\bar{\psi}(\partial\!\!\!/ + ie' A\!\!\!/' + im)\psi - \frac{\kappa}{2} B'^{\mu\nu} B_{\mu\nu}$$

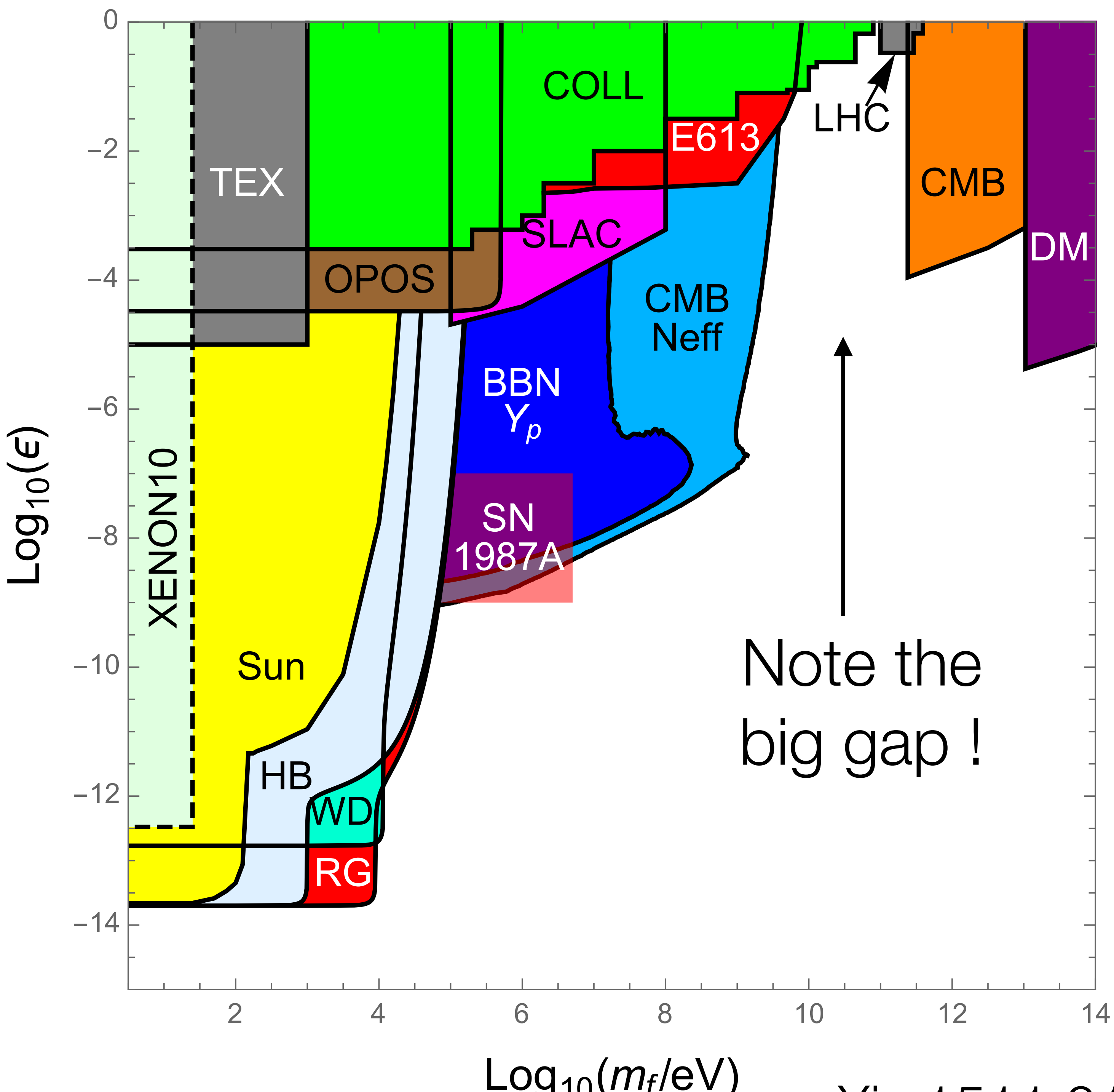
- Then re-define the gauge boson $B'_\mu \to B'_\mu + \kappa B_\mu$

$$\mathcal{L} = \mathcal{L}_{SM} - \frac{1}{4} B'^{\mu\nu} B'_{\mu\nu} + i\bar{\psi}(\partial\!\!\!/ + ie' A\!\!\!/' - i\kappa e' B\!\!\!/ + im)\psi$$

- The new fermion has a small electric charge, dependent on the kinetic mixing parameter

- Call this a ***milli-charged particle*** (or mCP)

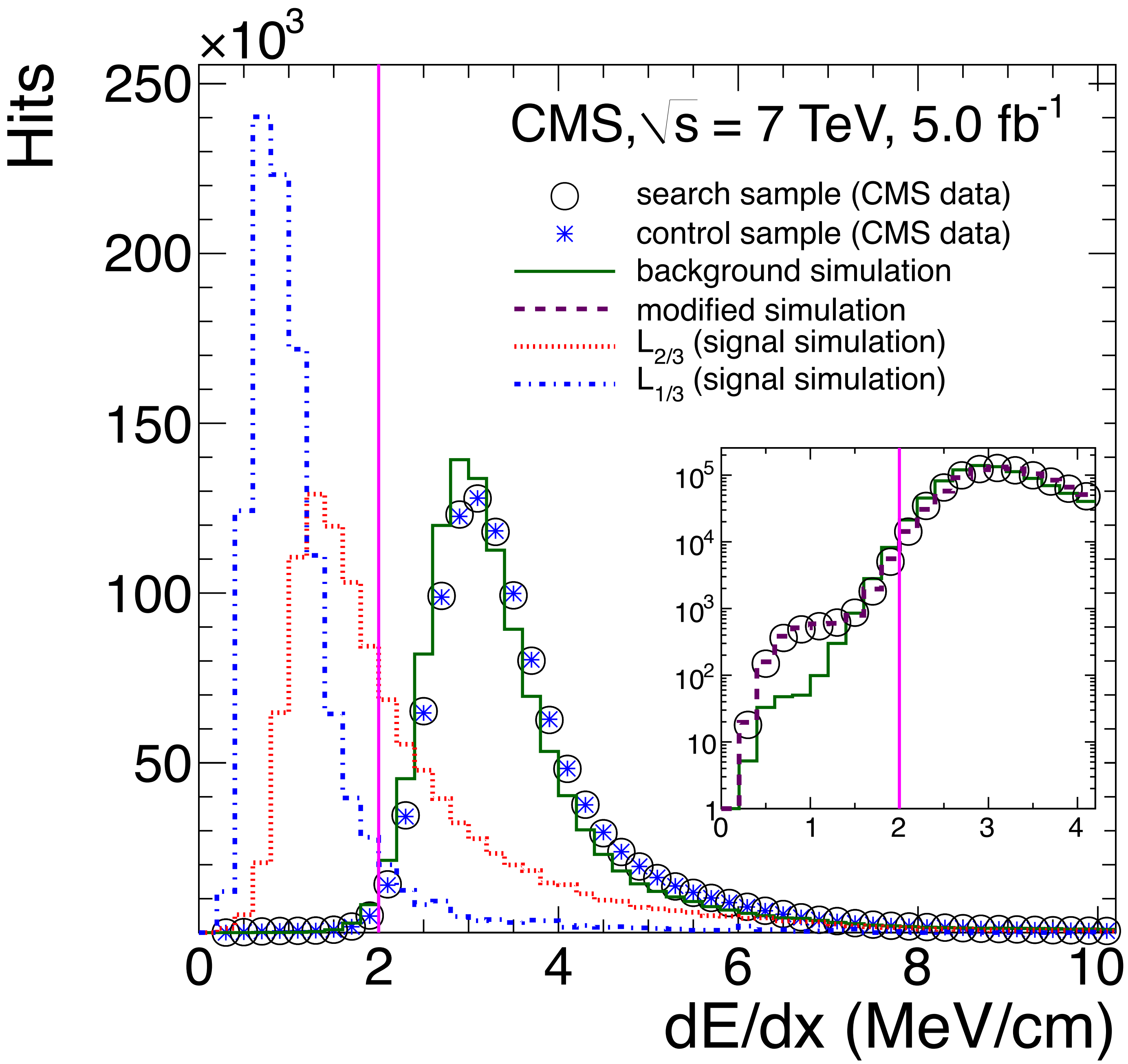
Existing Constraints on mCPs



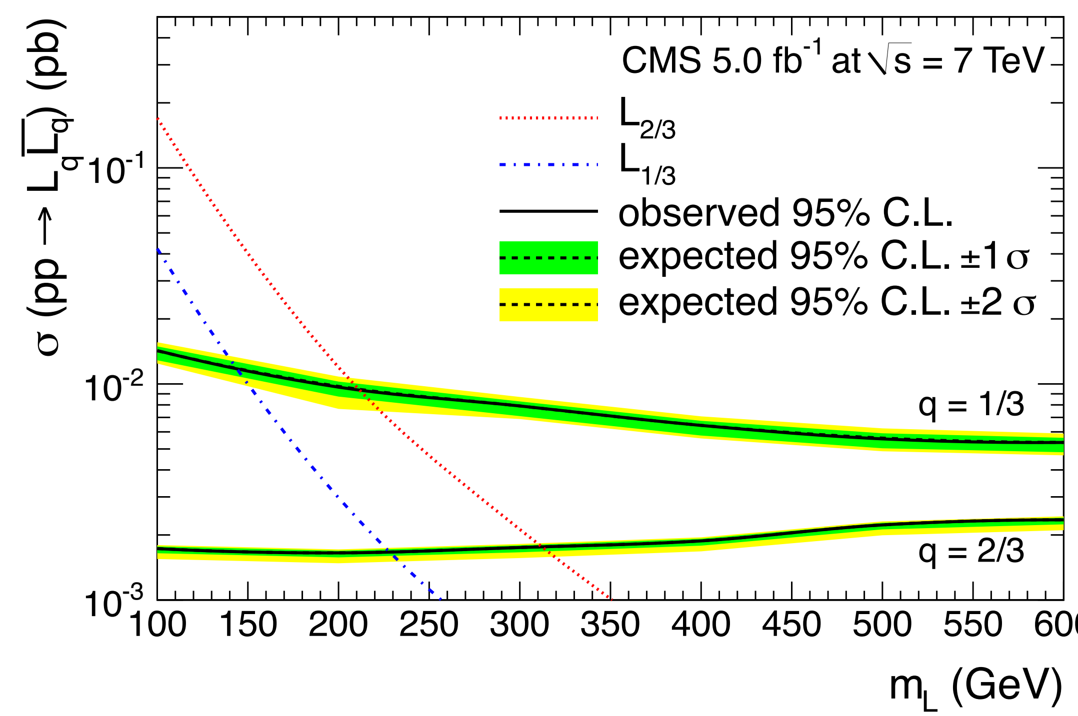
arXiv:1511.01122

- Cooling and energy loss from stars & SN
- Degrees of freedom in BBN & CMB
- Invisible decays of ortho-positronium
- Lamb-shift
- Collider/beam dump searches

LHC Results



- Searches for tracks with dE/dx below that for a q=1 MIP
- But tracking is designed for q=1
- Sensitivity limited to q>1/3

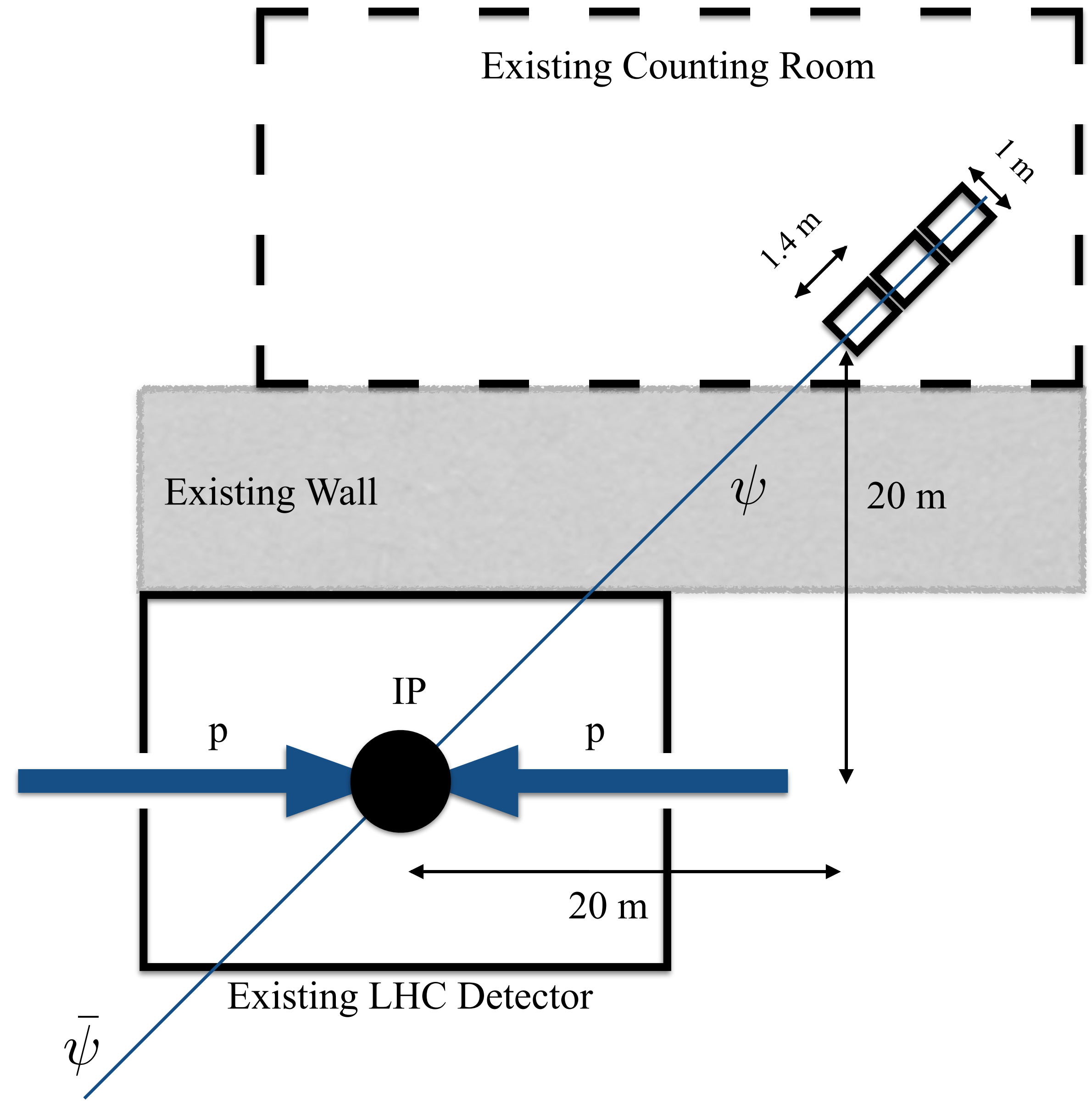


Improving Sensitivity to low charge

- Lower charge -> lower ionisation energy loss
- Need a large depth of sensitive material for the particle to traverse
  - -> increase probability of seeing a hit
- Make it sufficiently segmented to show the incident particle is compatible with the IP
- Look for evidence of ‘tracks’ that have dE/dx lower than that of a q=1 MIP

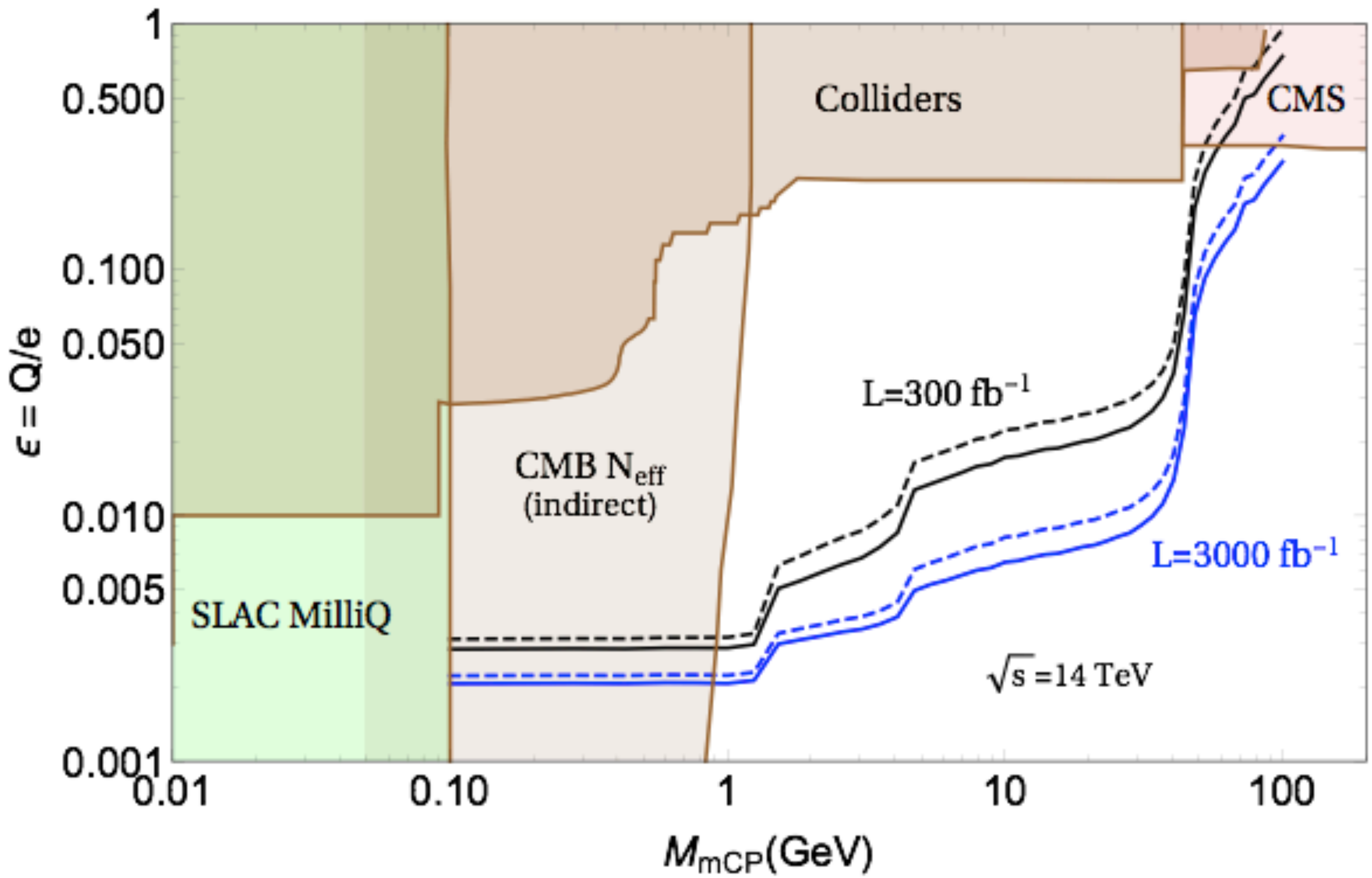
Proposed Search

- Original authors proposed a dedicated experiment
    - Three-layered scintillator array
    - Background reduced by large amount of rock shielding
- Detect mCP by looking for IP-pointing triple-incidence of low light signals
    - Q=1 will give much bigger signal
    - Backgrounds assumed to arise solely from PMT dark counts



Haas, Hill, Izaguirre, Yavin PLB 746 (2015)

Proposed Search



Haas, Hill, Izaguirre, Yavin PLB 746 (2015)

MilliQan Collaboration

- Austin Ball[1], Jim Brooke[2], Claudio Campagnari[3], Albert De Roeck[1], Brian Francis[4], Martin Gastal[1], Frank Golf[3], Joel Goldstein[2], Andy Haas[5], Christopher S. Hill[4], Jim Hirschauer[10], Eder Izaguirre[6], Benjamin Kaplan[5], Stephen Lowette[12], Gabriel Magill[7,6], Bennett Marsh[3], David Miller[8], Chris Neu[9], Theo Prins[1], Harry Shakeshaft[1], David Stuart[3], Max Swiatlowski[8], Itay Yavin[7,6], and Haitham Zaraket[11]

Letter Of Intent

arXiv:1607.04669

- LOI published in July 2016
    - Location identified
    - Relationship with CMS understood
    - Full detector simulation
    - Updated sensitivity

A Letter of Intent to Install a Milli-charged Particle Detector at LHC P5

Austin Ball,[1] Jim Brooke,[2] Claudio Campagnari,[3] Albert De Roeck,[1] Brian Francis,[4] Martin Gastal,[1] Frank Golf,[3] Joel Goldstein,[2] Andy Haas,[5] Christopher S. Hill,[4] Eder Izaguirre,[6] Benjamin Kaplan,[5] Gabriel Magill,[7,6] Bennett Marsh,[3] David Miller,[8] Theo Prins,[1] Harry Shakeshaft,[1] David Stuart,[3] Max Swiatlowski,[8] and Itay Yavin[7,6]

[1]*CERN*
[2]*University of Bristol*
[3]*University of California, Santa Barbara*
[4]*The Ohio State University*
[5]*New York University*
[6]*Perimeter Institute for Theoretical Physics*
[7]*McMaster University*
[8]*University of Chicago*

(Dated: July 19, 2016)

Abstract

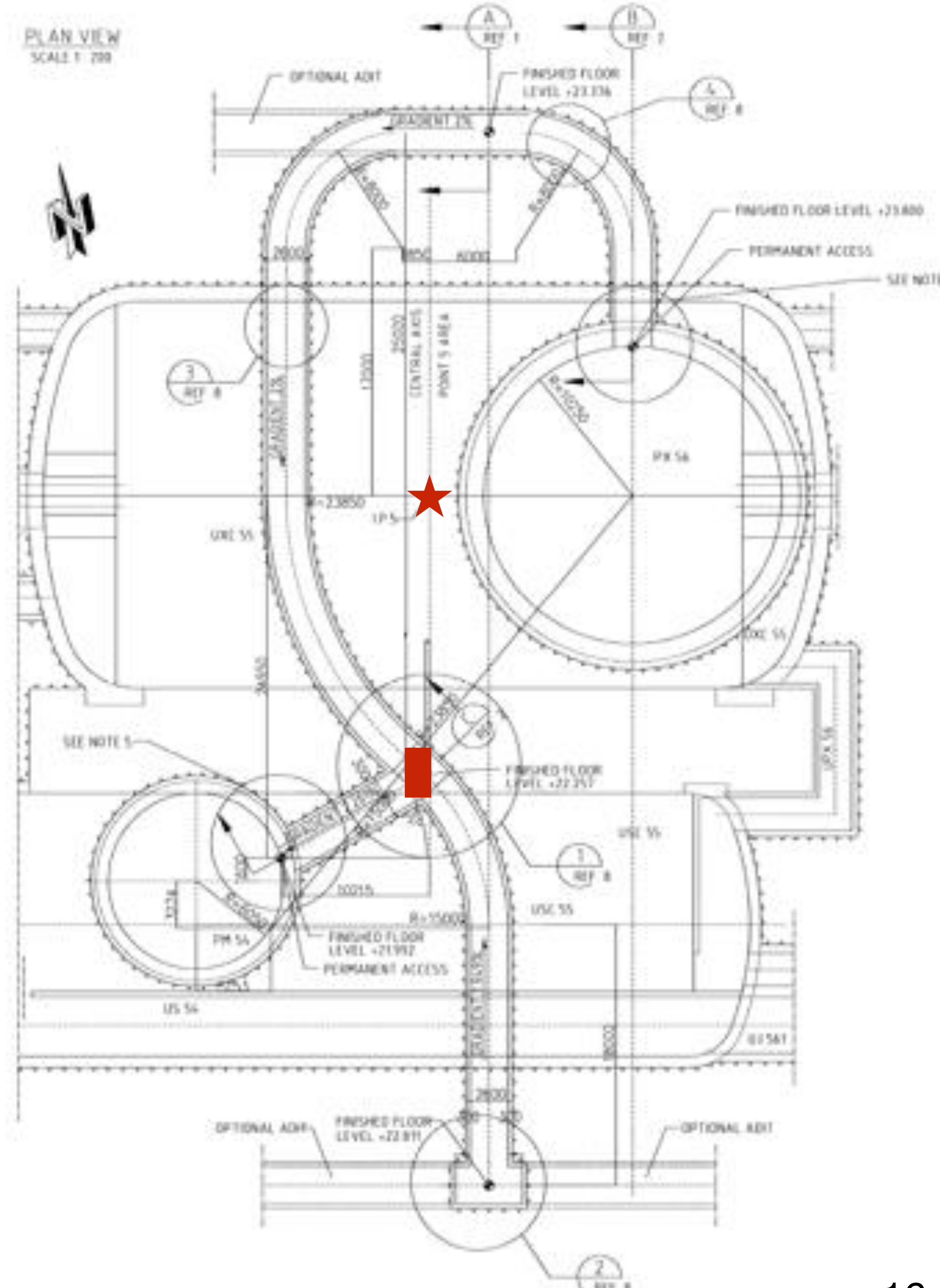
In this LOI we propose a dedicated experiment that would detect "milli-charged" particles produced by pp collisions at LHC Point 5. The experiment would be installed during LS2 in the vestigial drainage gallery above UXC and would not interfere with CMS operations. With 300 fb^{-1} of integrated luminosity, sensitivity to a particle with charge $\mathcal{O}(10^{-3})$ e can be achieved for masses of $\mathcal{O}(1)$ GeV, and charge $\mathcal{O}(10^{-2})$ e for masses of $\mathcal{O}(10)$ GeV, greatly extending the parameter space explored for particles with small charge and masses above 100 MeV.

Location, Location, Location

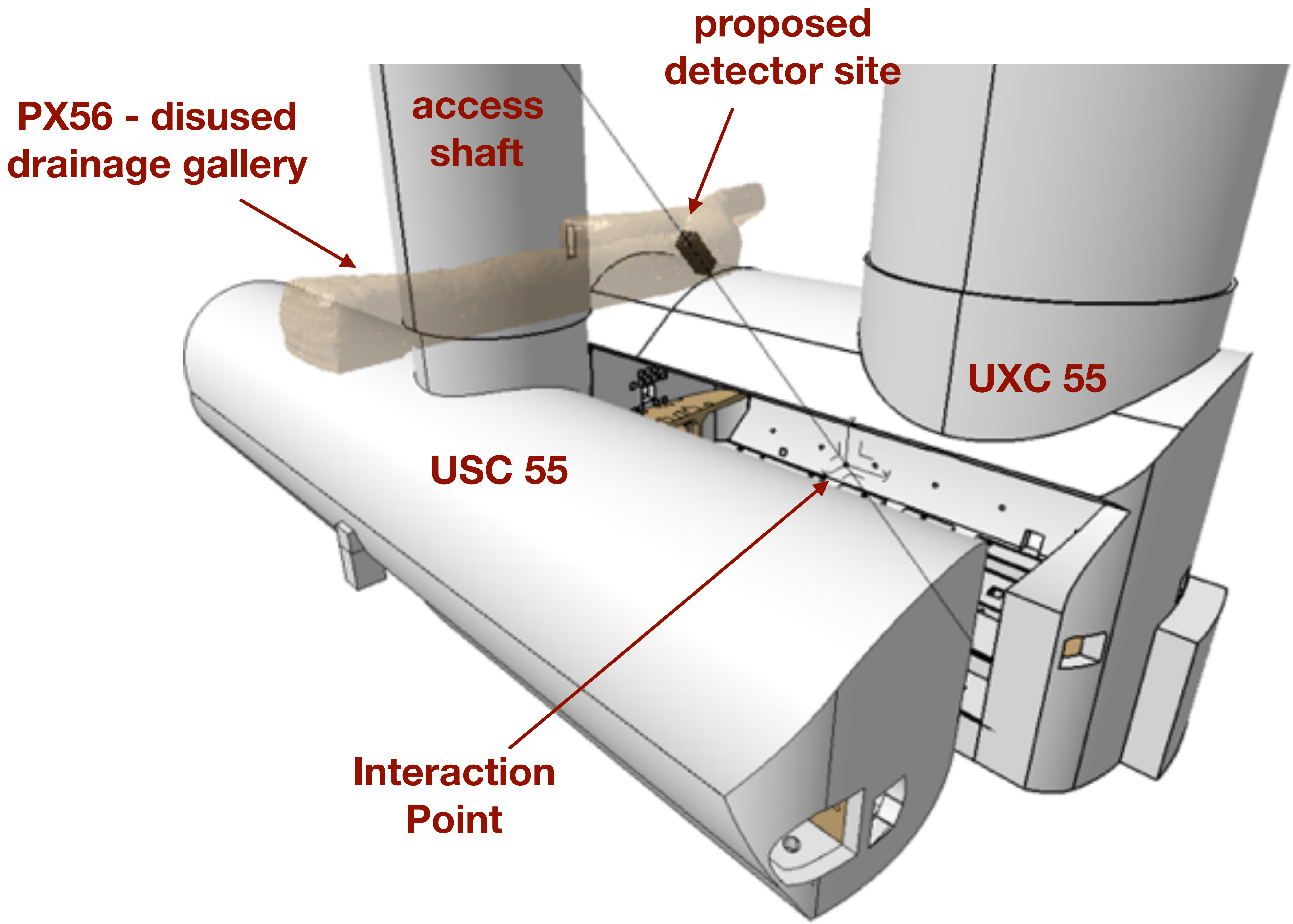
- Constraints:
    - Near LHC P1 or P5 for maximum luminosity
    - Behind at least 5m of concrete, based on previous tests in CMS counting room
    - Space to accommodate the detector ~ 1m x 1m x 3m
    - Floor loading to be compatible with detector and its support structure ~3500kg - 6000kg
    - Power supply available, with possibility to add other network etc.
    - Selected experimental area should remain clear of “visitors” during data taking

- Many sites near P1 and P5 considered - eventually settled on PX56

Location, Location, Location

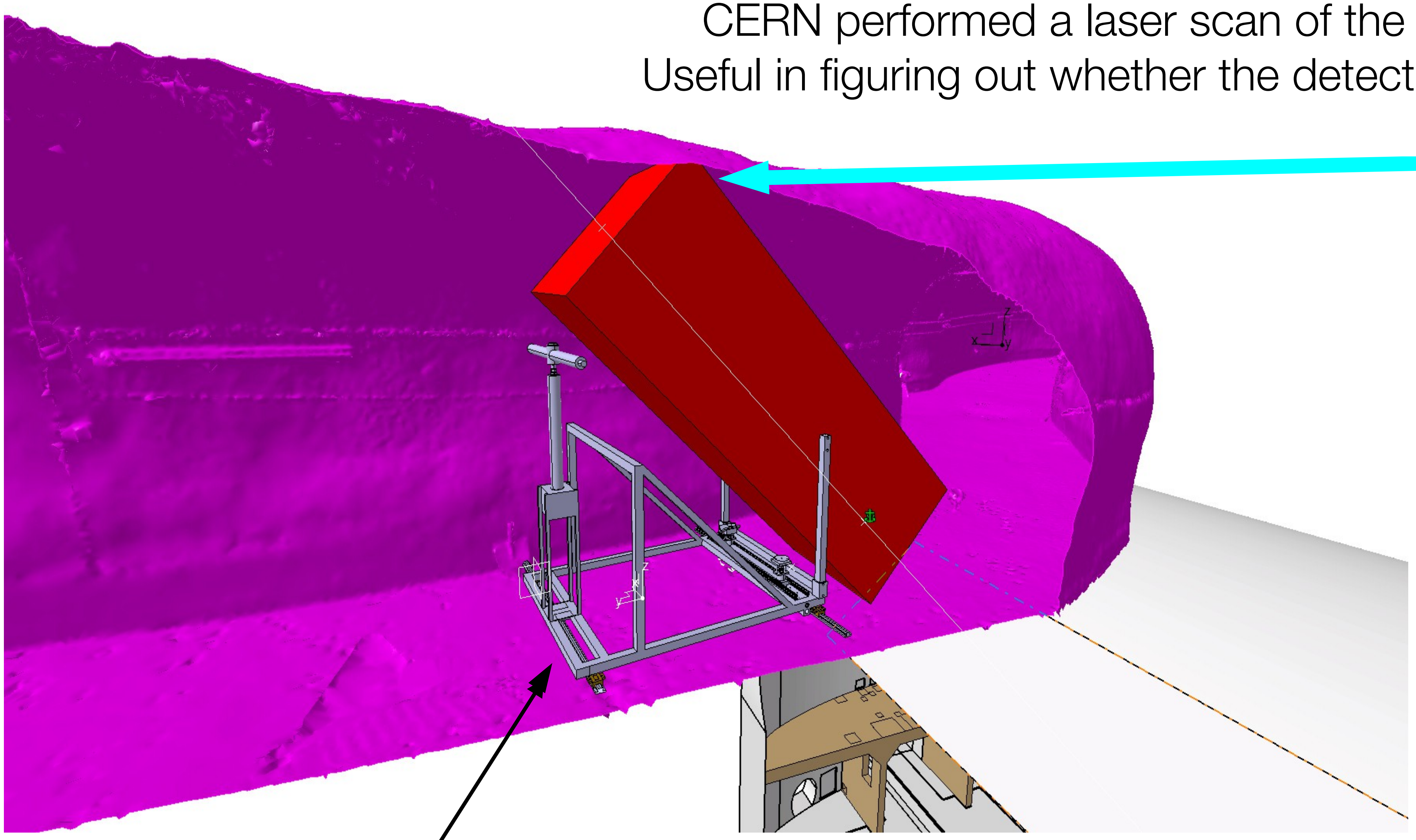


Location, Location, Location



Tunnel Survey

CERN performed a laser scan of the tunnel
Useful in figuring out whether the detector will fit !

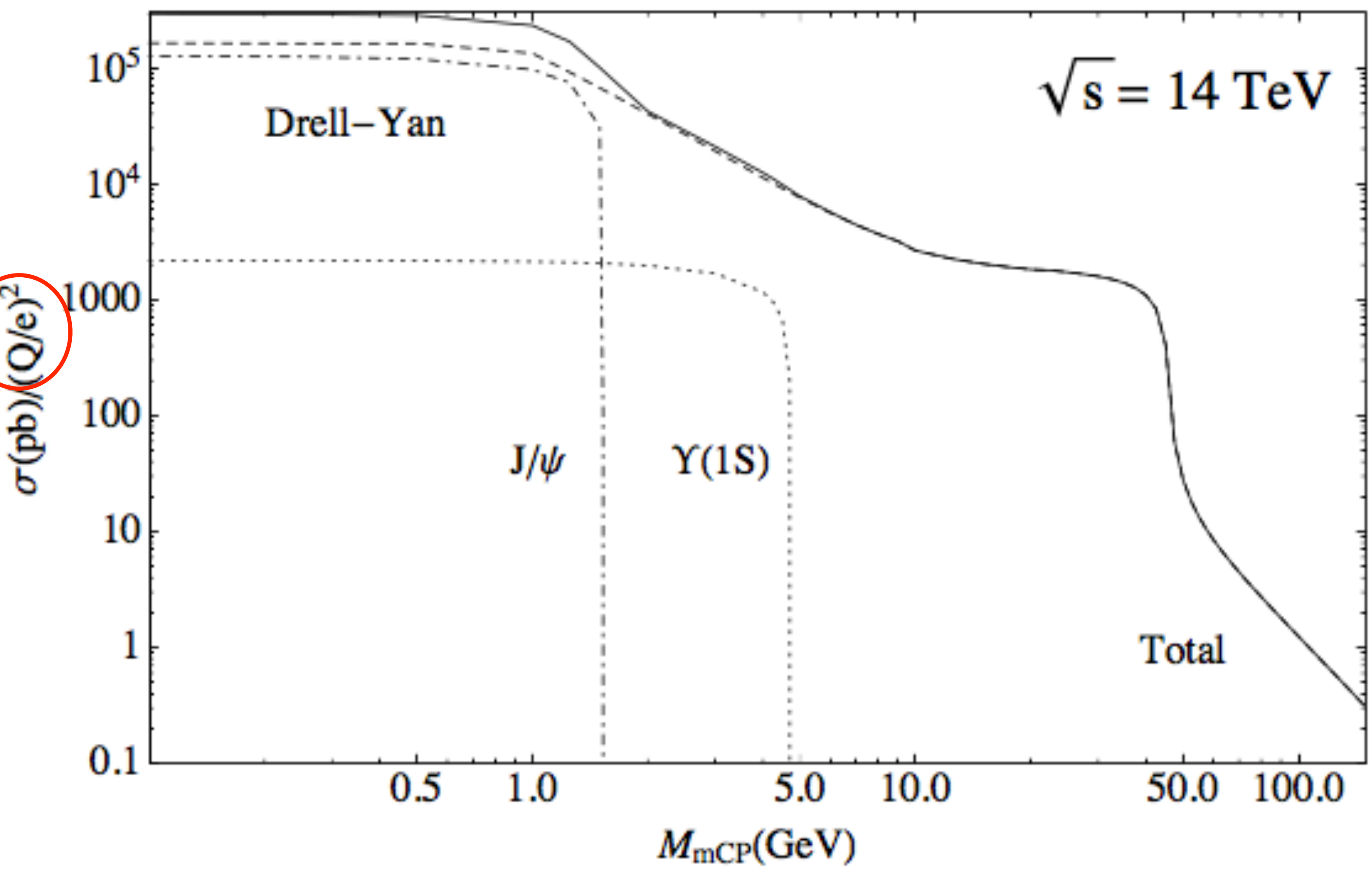


CERN & Lebanese University also designed a support structure
that would allow the whole array to be aligned toward the IP

Tunnel Survey

- CERN team have extended the CMS coordinate system to PX56
- Expect to align MilliQan with ~2cm precision

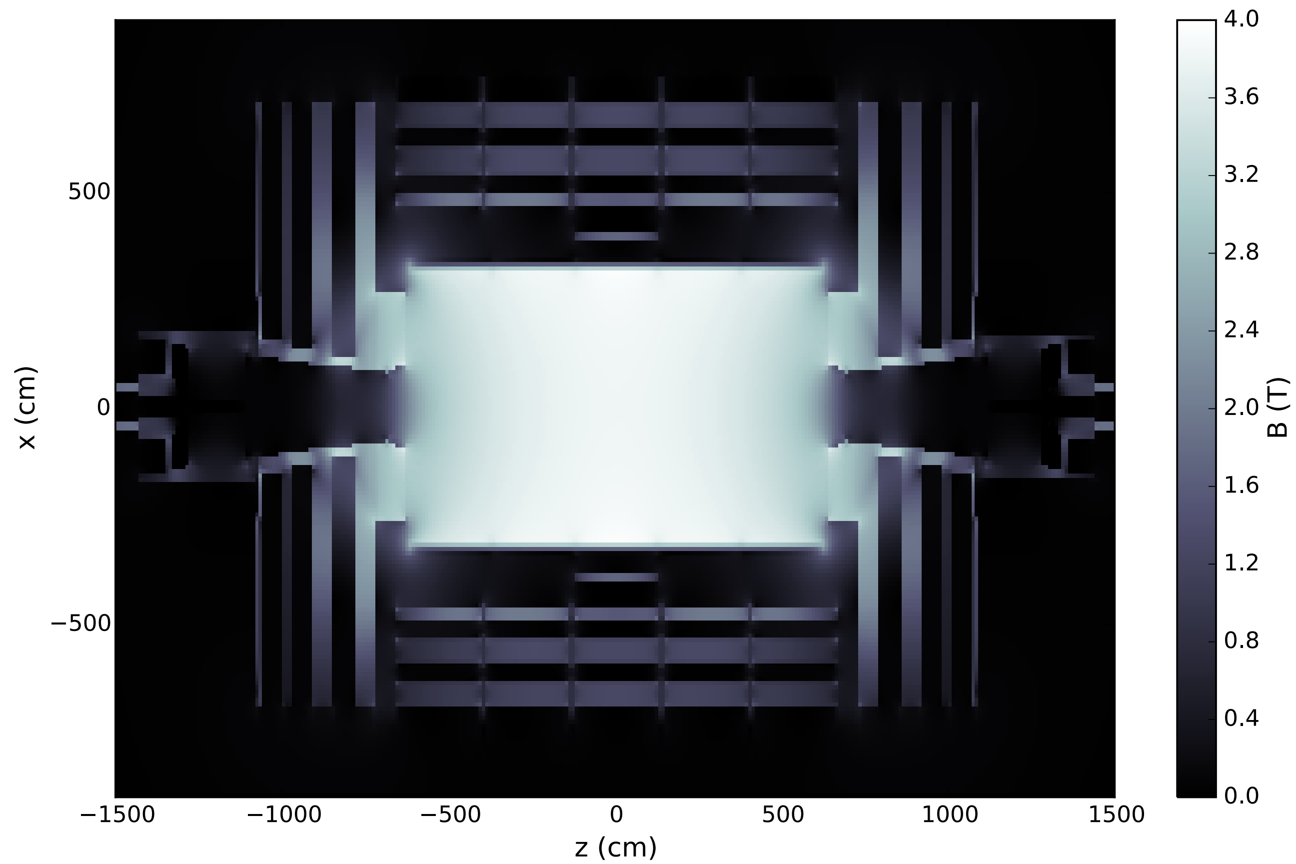
mCP Production Cross-Section

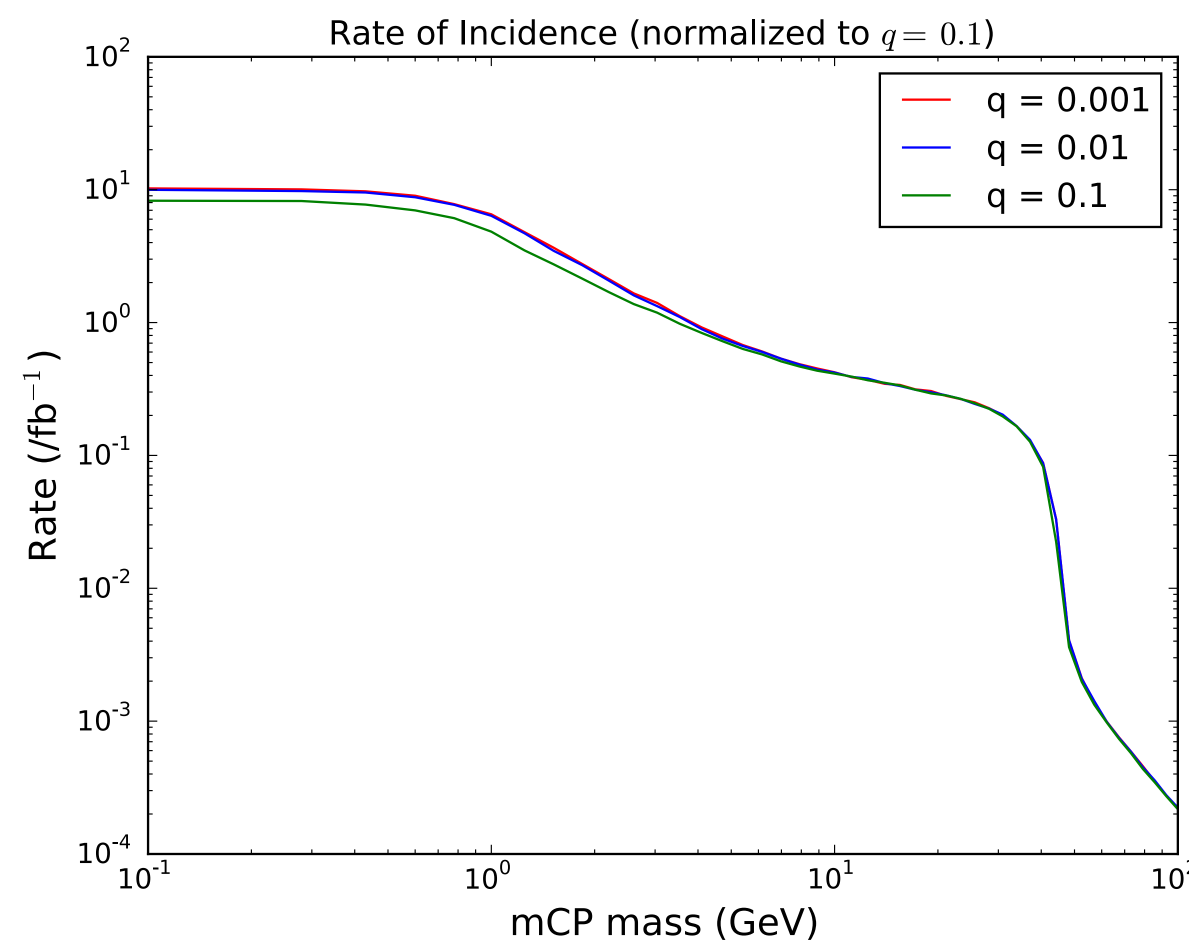


$$pp \to \psi\bar{\psi} + X$$

Note the proportionality to q^2 !

Simulation



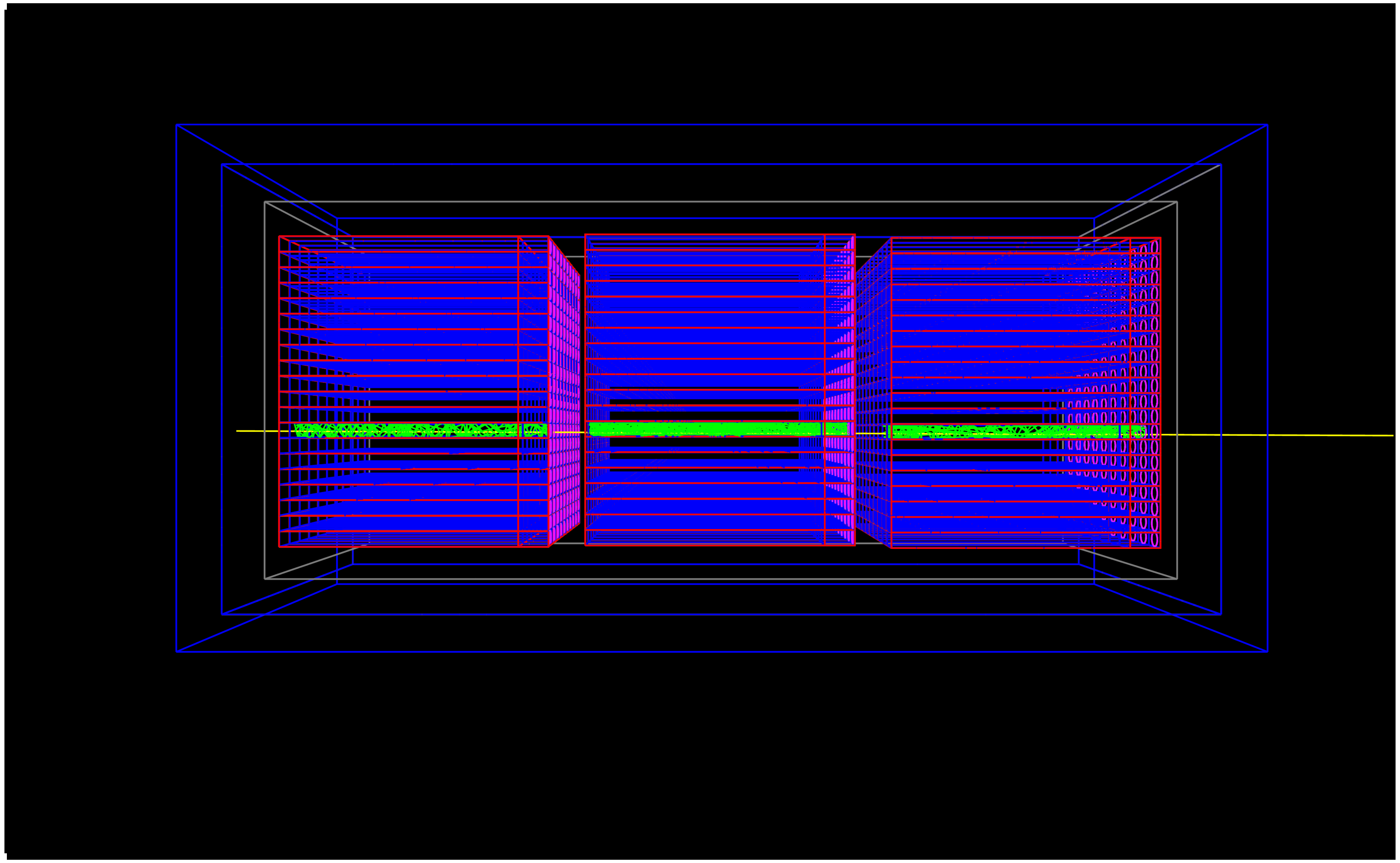


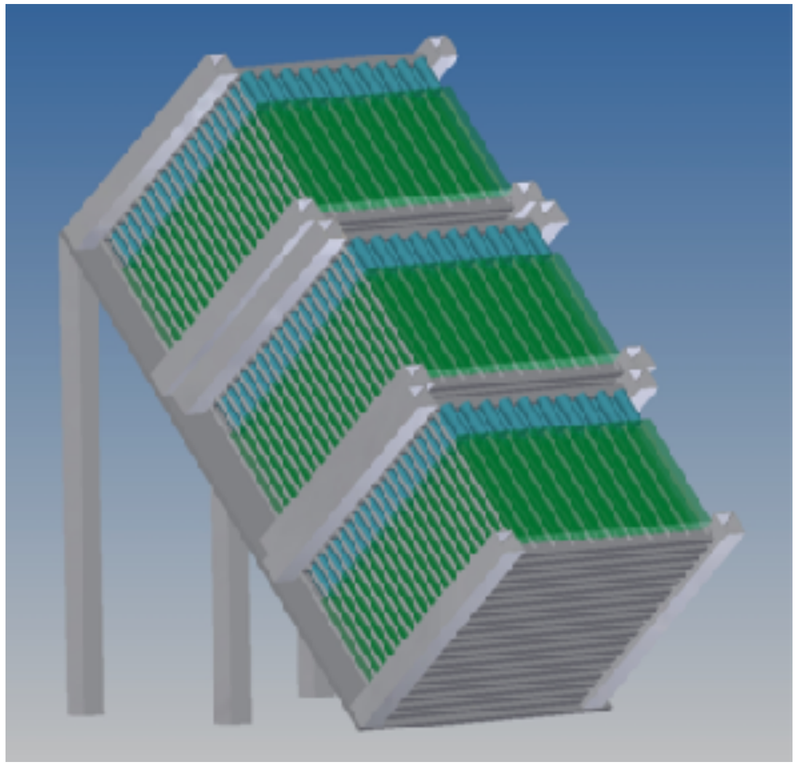
- Simulate mCP production via Drell-Yan, j/ψ, Υ. Cross-section ∝ q^2
- Propagate through CMS magnetic field
- Simulate interactions with rock, calculate rate of mCP incidence at detector

arXiv:1607.04669

Simulation

- Full GEANT4 simulation : reflectivity, attenuation, shape of scintillator.
- We input quantum efficiency, scintillator light spectrum, time constants, digitised waveforms



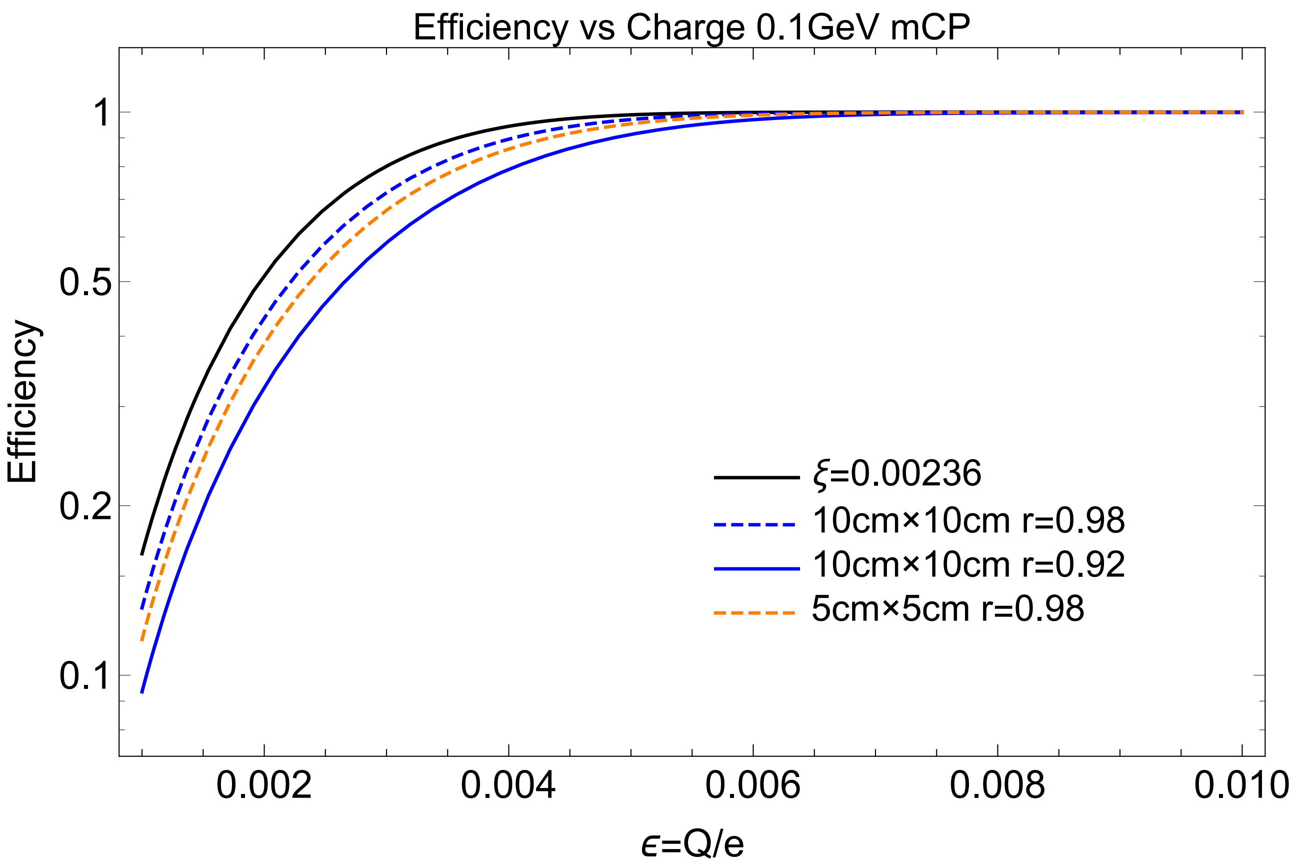


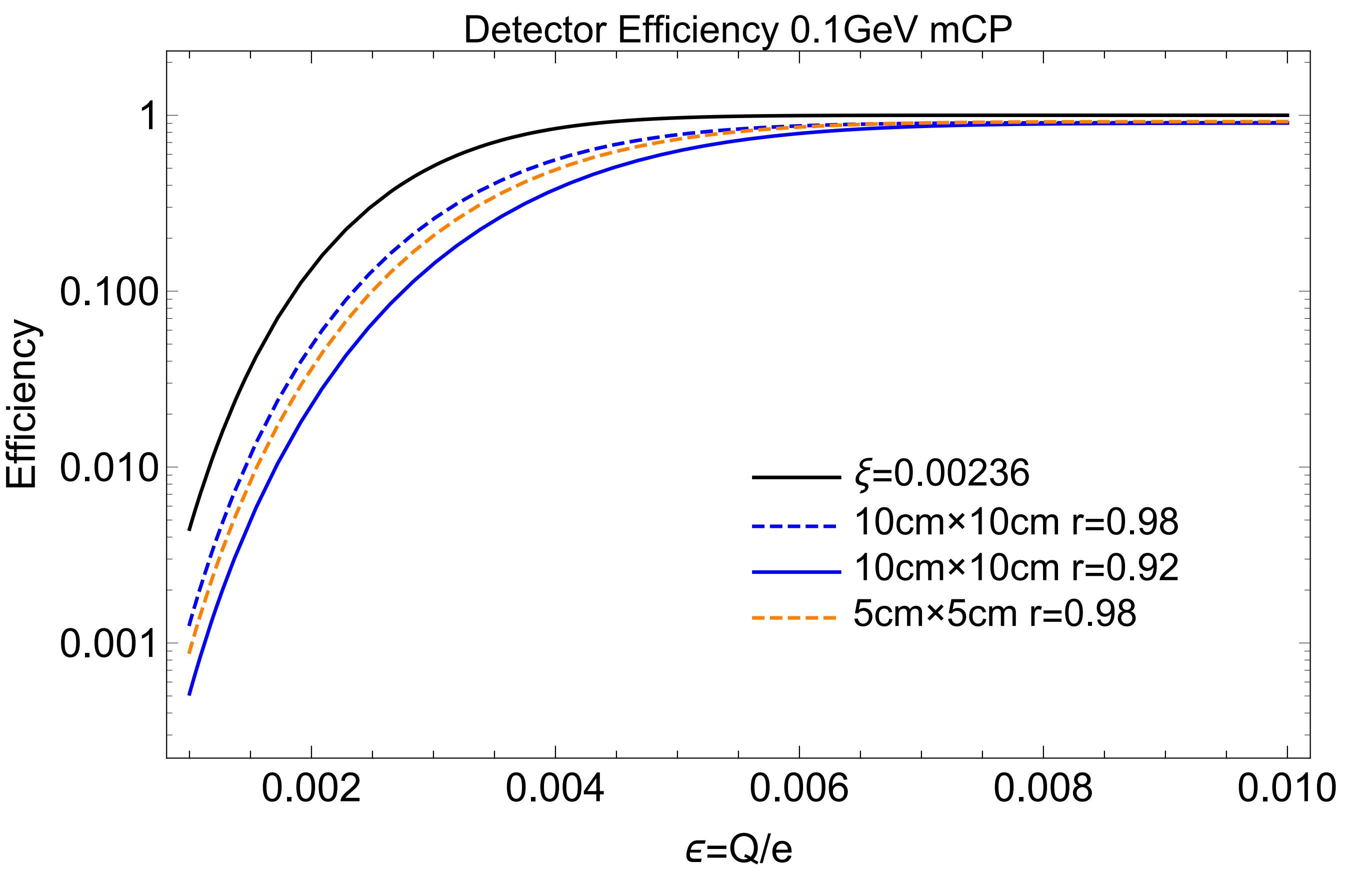
Simulation of a single mCP event ←

⟨nPE⟩ = 1 for
Q = 0.003e

arXiv:1607.04669

Simulation

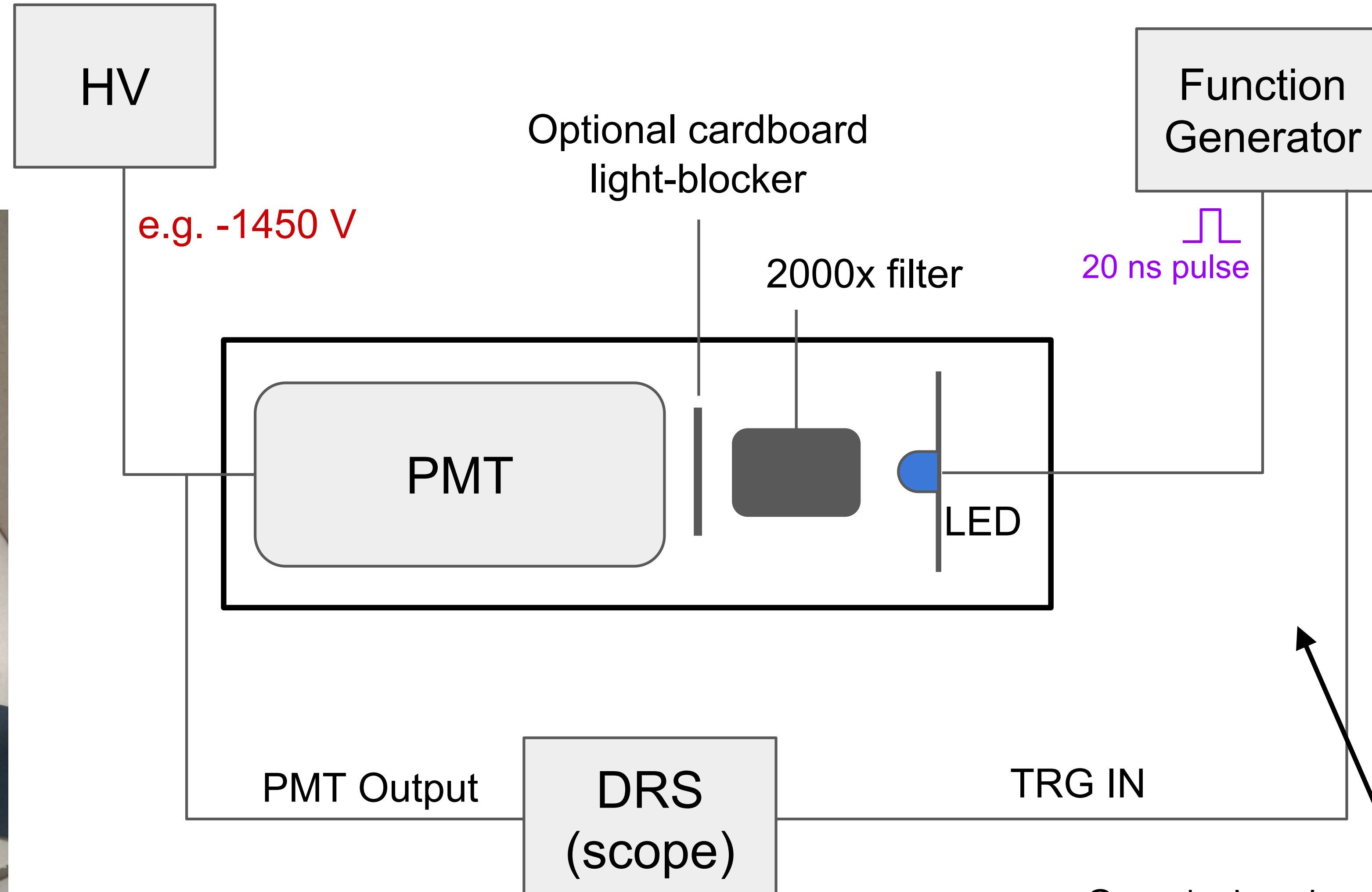




- Efficiency to produce > 1PE in a single bar (L) and full detector (R)
- Black line is parameterisation used in original paper
- Red/blue show GEANT4 results for different reflectivity/dimensions

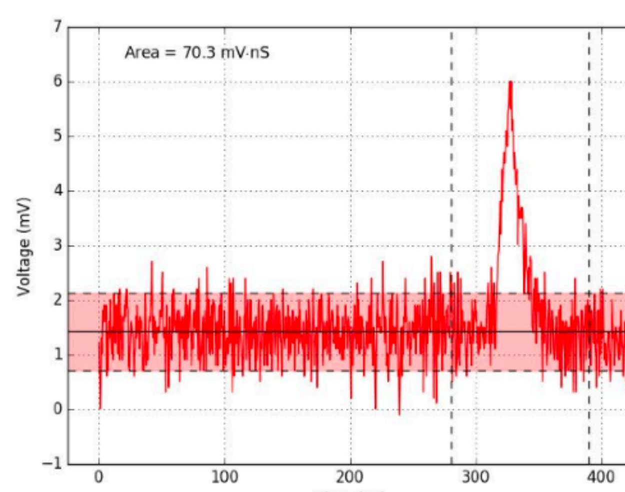
arXiv:1607.04669

SPE calibration using LED



Send simultaneous
LED pulse and trigger

Digitise and record waveforms



Measure pulse area
using integral of window

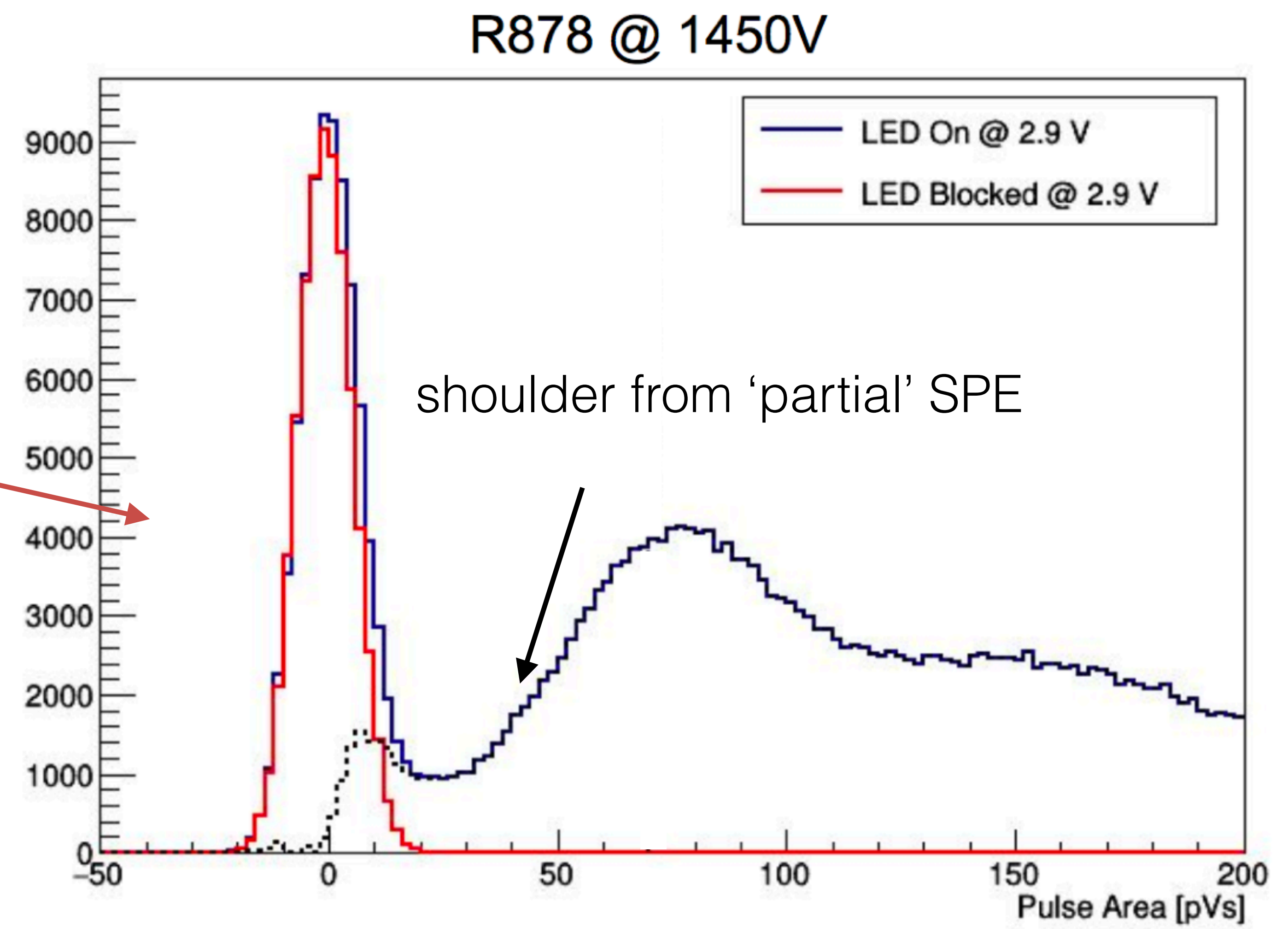
Will show results for example PMT (R878)

SPE calibration using LED

First find average NPE from LED

Use 'LED blocked' dataset to measure 0 PE template

Scale to match left edge of LED unblocked (area < 0)



Input N_{PE} from LED is poisson distributed:

$$< N_{PE} > = -\log(\text{events}_{N=0}/\text{events})$$

for this LED (at this voltage) find $< N_{PE} > = 1.71$

method from Saldanha et al., https://arxiv.org/abs/1602.03150

SPE calibration using LED

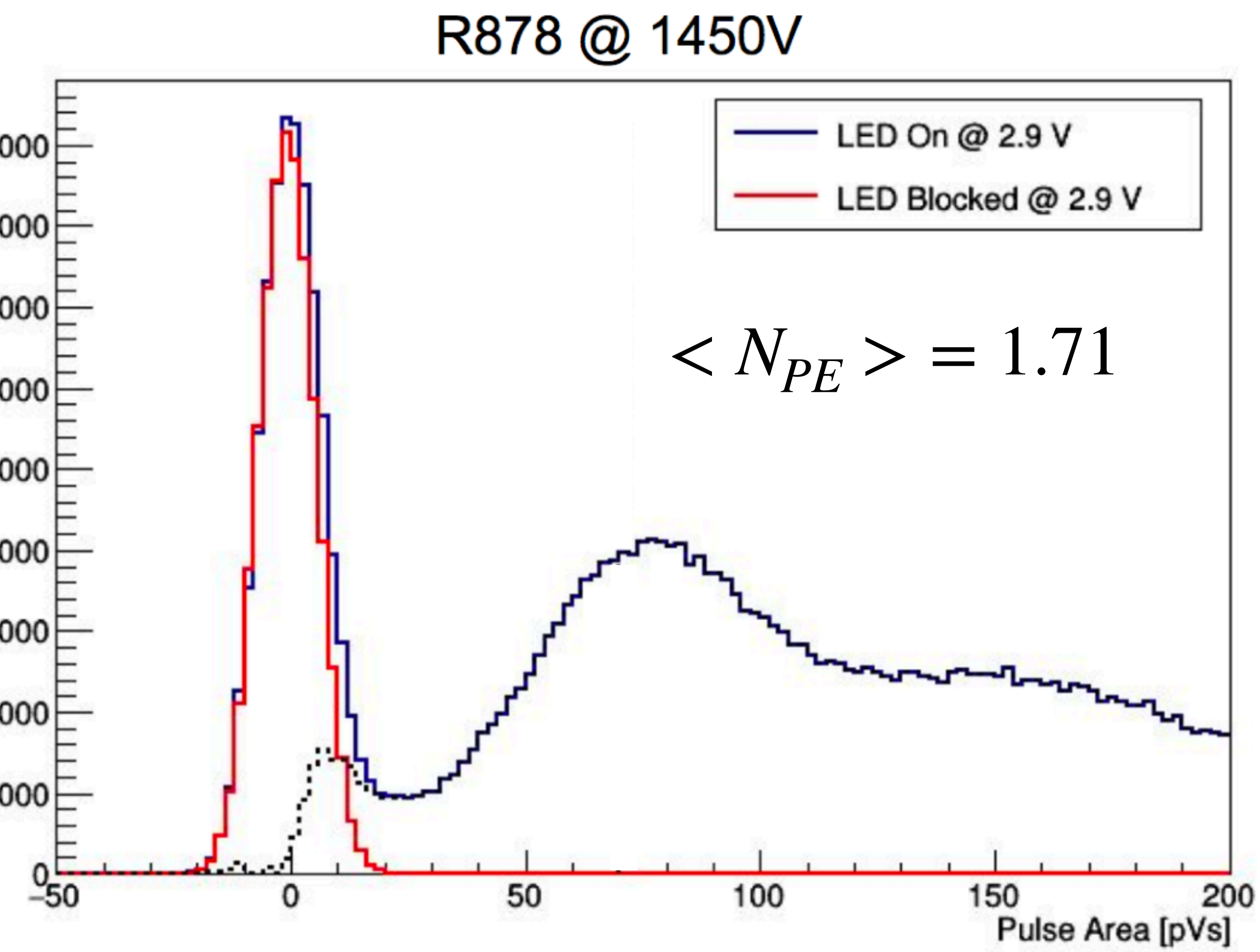
Now calculate SPE area

Only assume linear PMT response (true for low NPE)

$$< A_{SPE} > = \frac{< A_{\text{LED on}} > - < A_{\text{pedestal}} >}{< N_{PE} >}$$

Similar trick to find σ

no functional form assumed for area of SPE or pedestal!



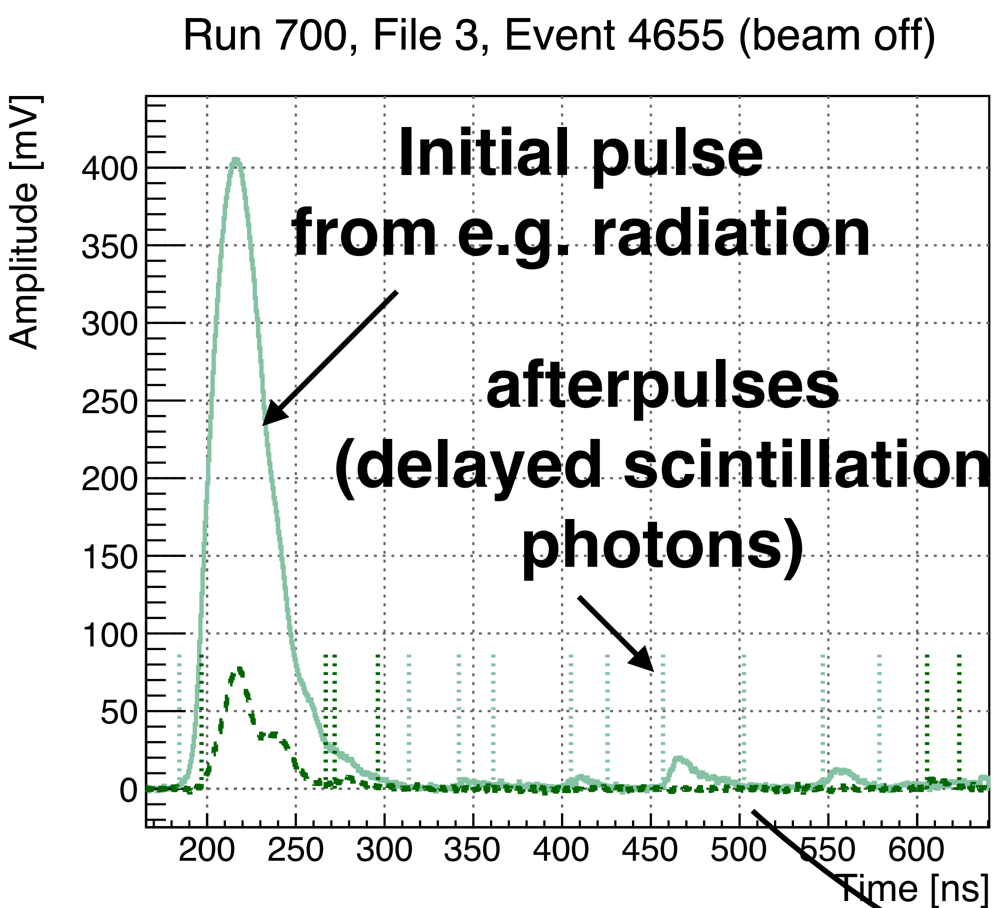
For this PMT (at 1450V):

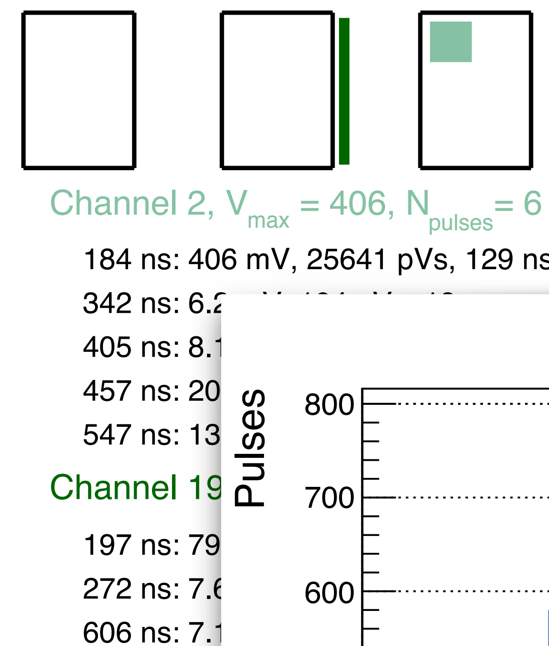
$$< A_{SPE} > = 69.9 \text{ pVs}$$

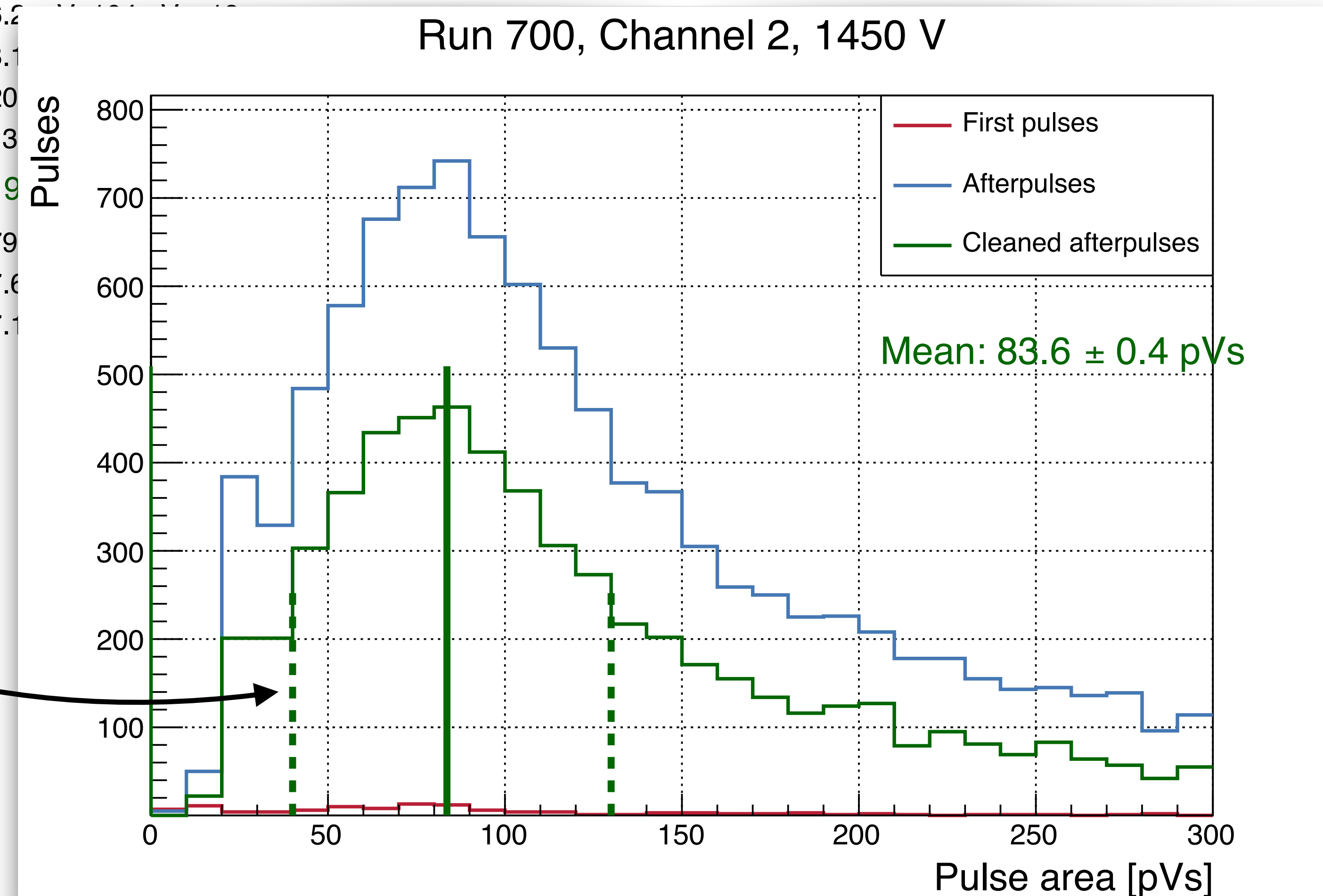
$$\sigma = 32 \text{ pVs}$$

method from Saldanha et al., https://arxiv.org/abs/1602.03150

Calibration from delayed scintillation pulses





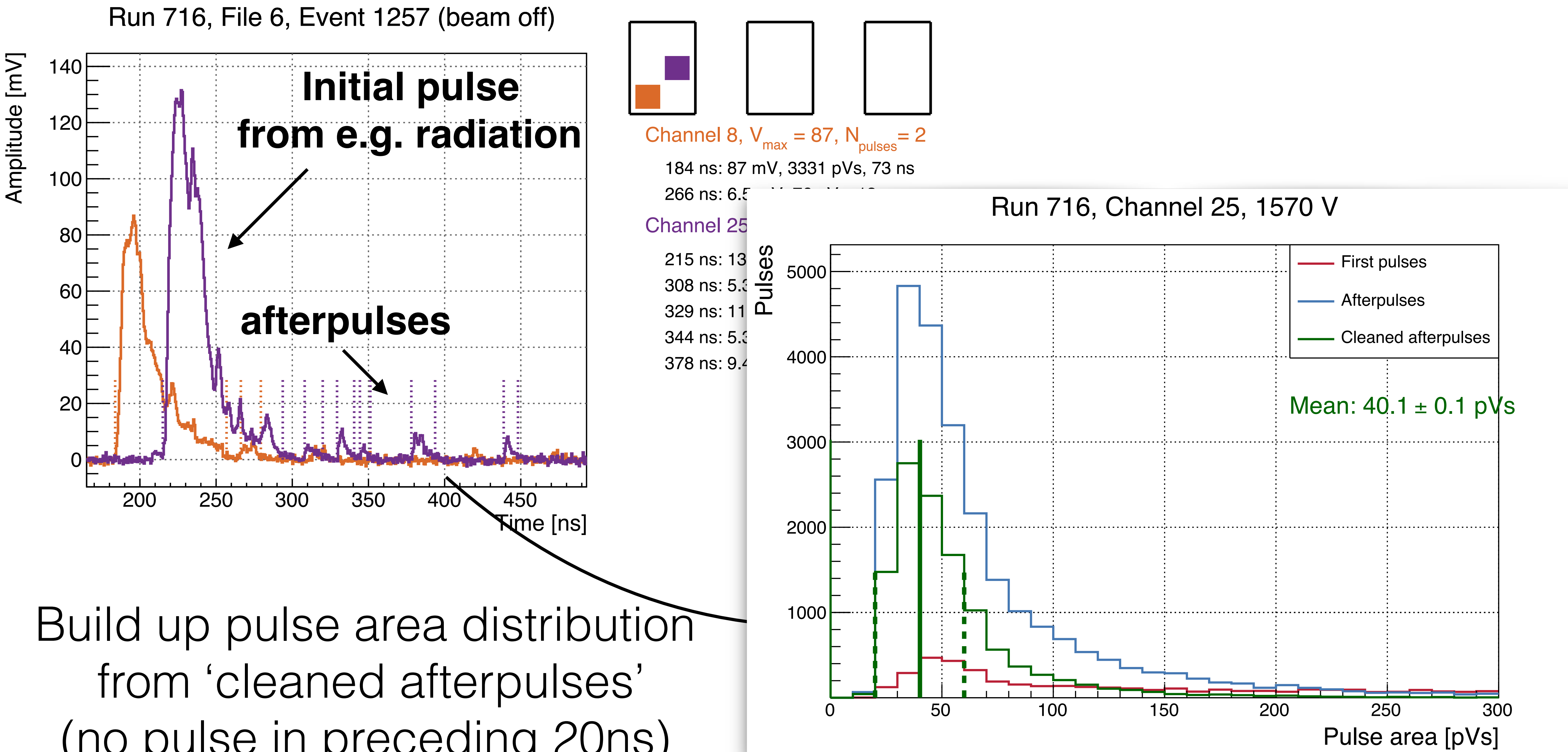


Build up pulse area distribution from ‘cleaned afterpulses’ (no pulse in preceding 20ns)

e.g. R878 PMT

Mean within half-width-max gives SPE pulse area

Calibration from delayed scintillation pulses



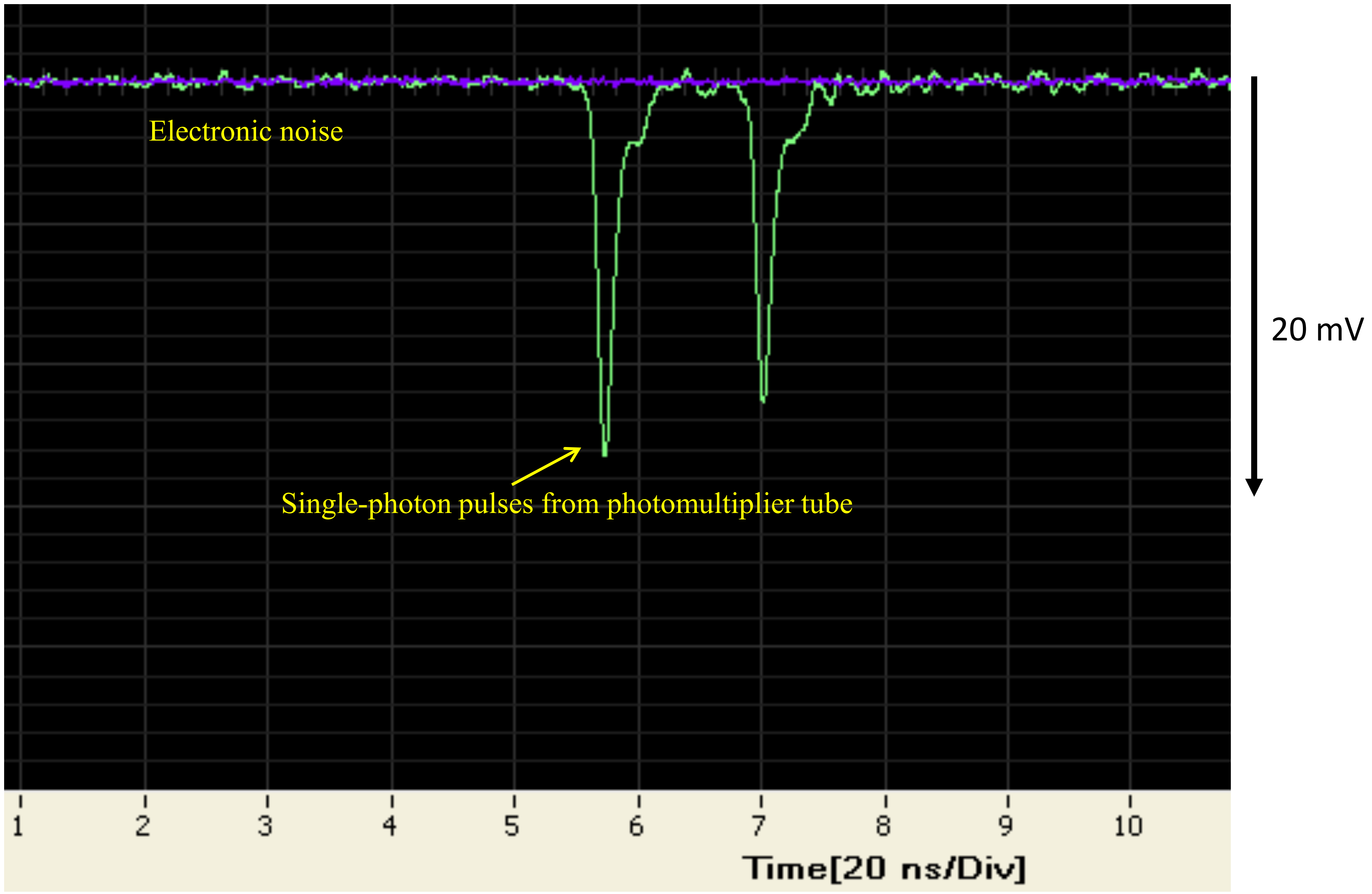
Build up pulse area distribution from ‘cleaned afterpulses’ (no pulse in preceding 20ns)

e.g. ET9814B PMT

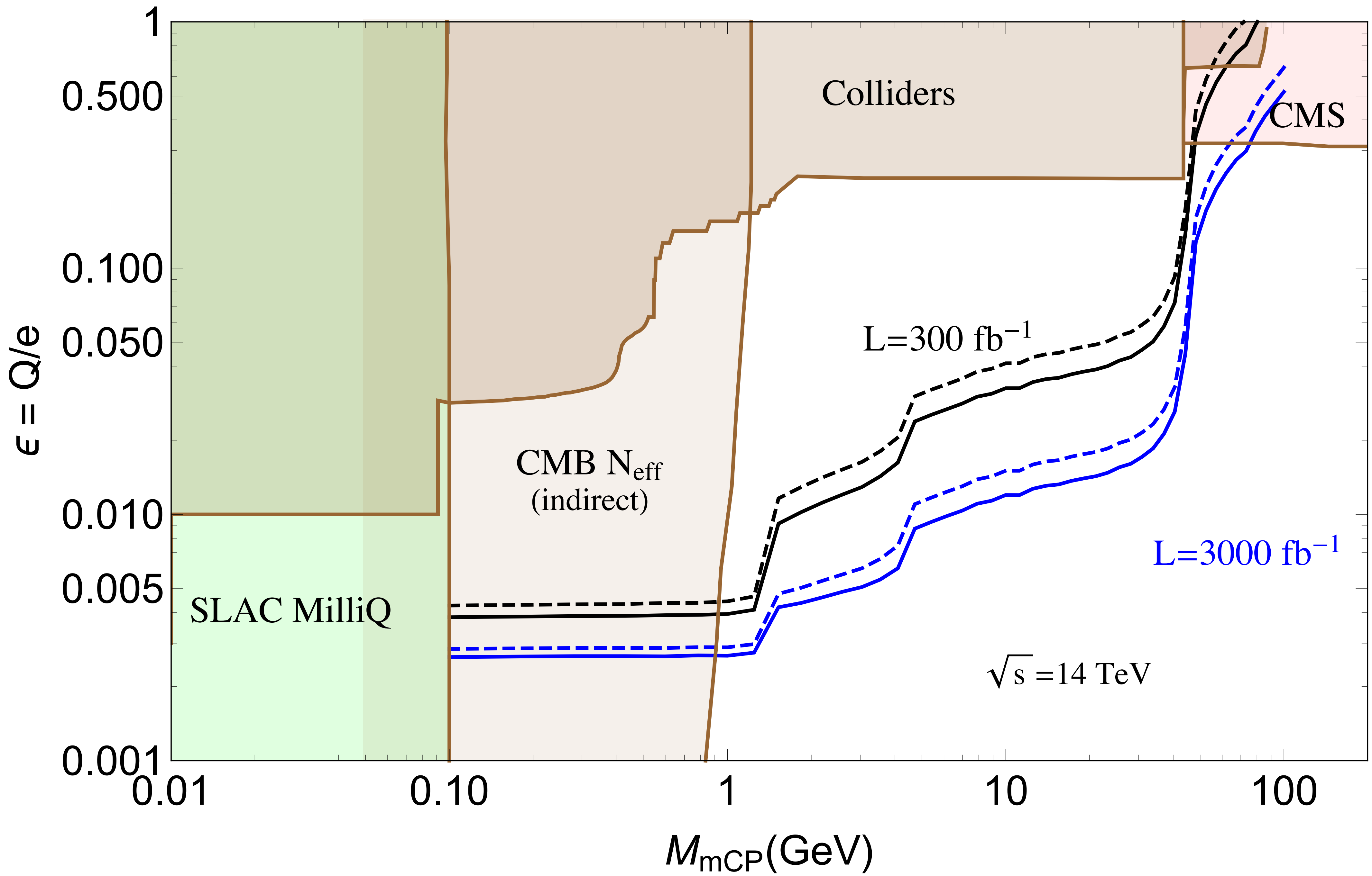
Mean within half-width-max gives SPE pulse area

Single Photon Pulses

Fantastic detail of each photomultiplier pulse from a triggered event
~1 ns timing resolution, even for tiny (single photon) pulses



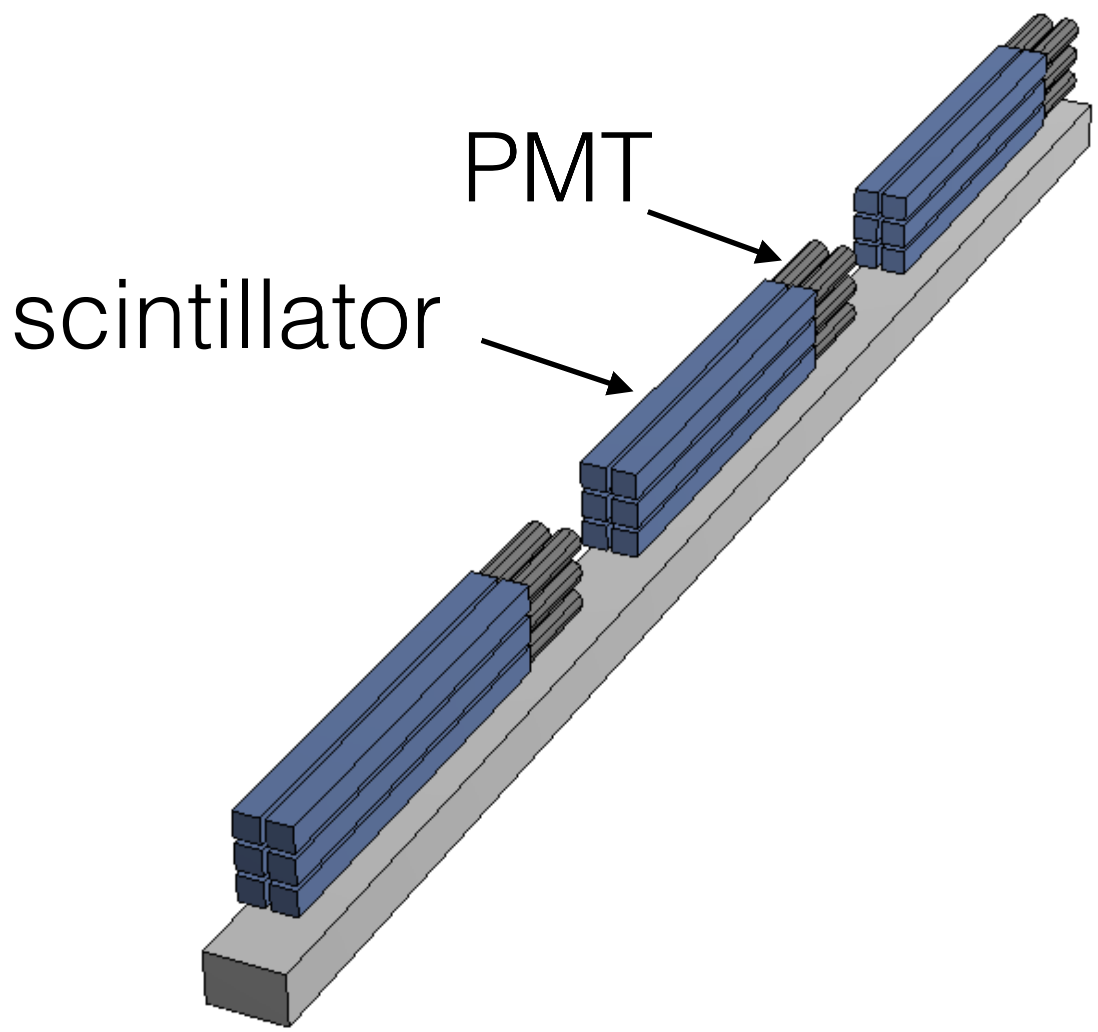
Predicted Sensitivity



arXiv:1607.04669

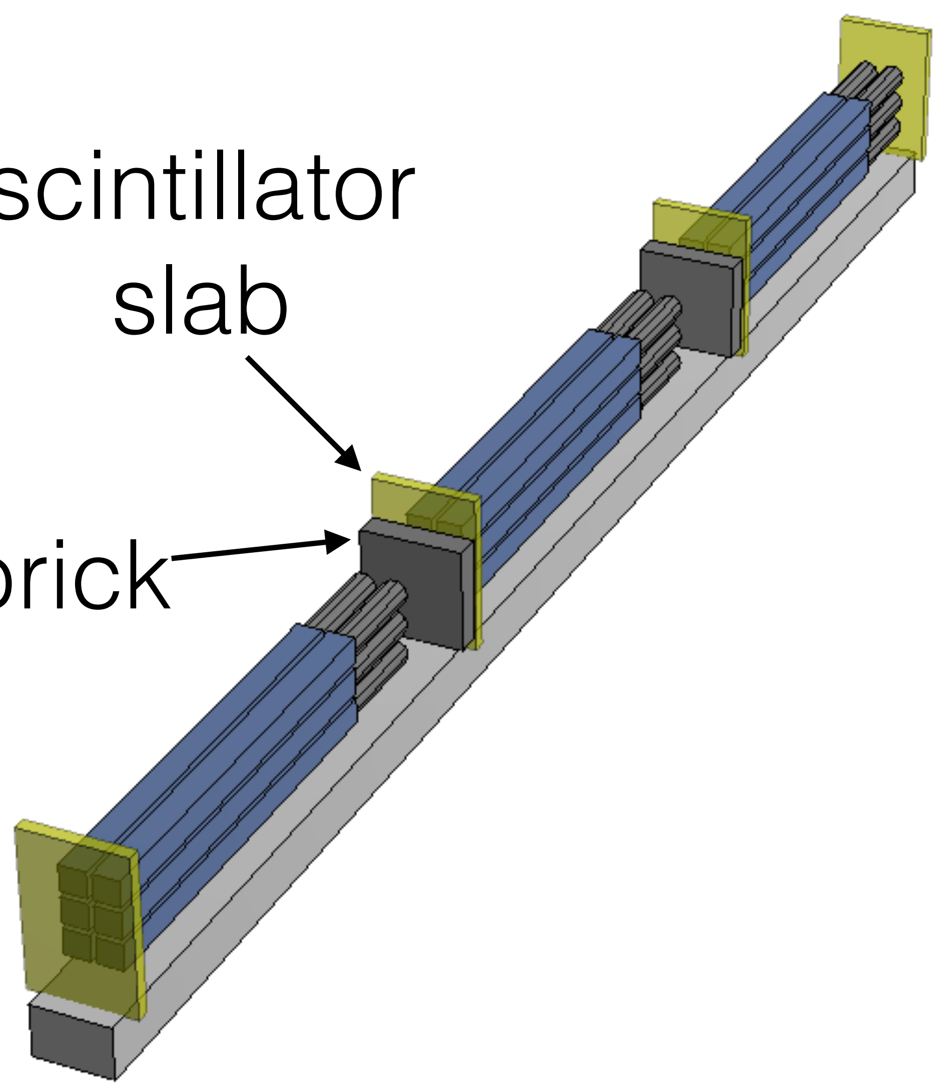
MilliQan Demonstrator

MilliQan Demonstrator



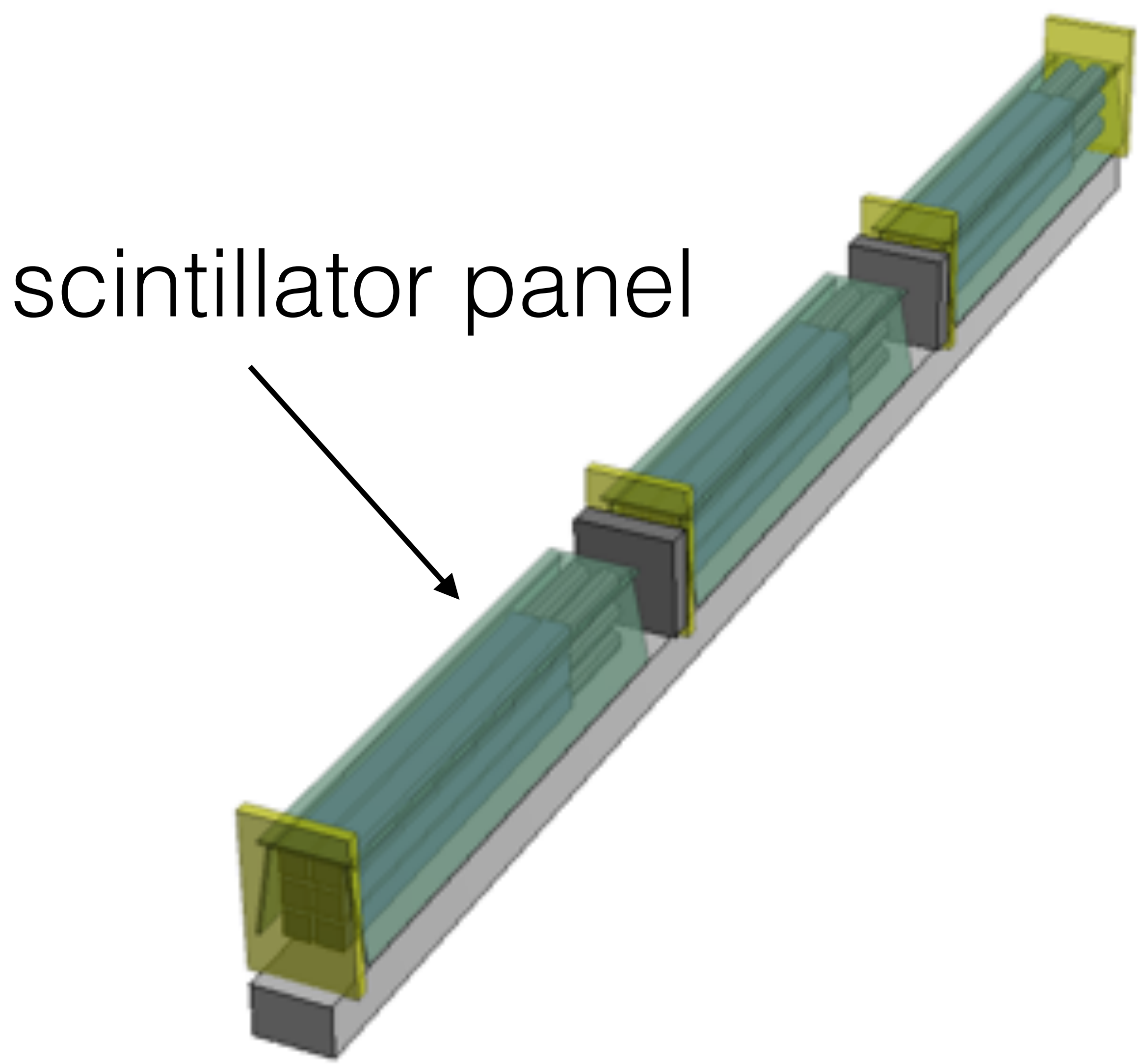
- 3 layers of 2x3 scintillator+PMT
  - ~ 1% prototype of full milliQan detector

MilliQan Demonstrator



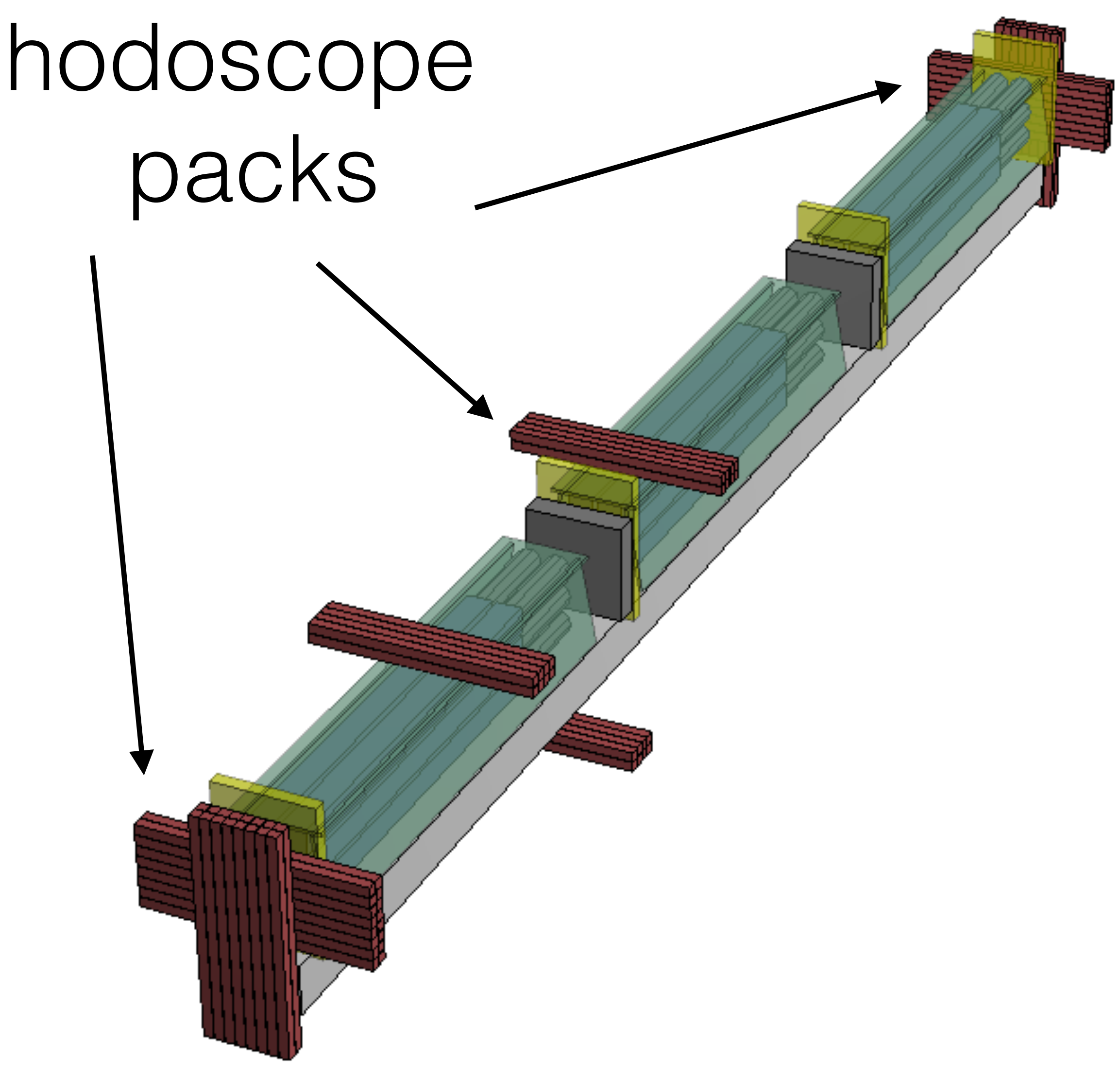
- 3 layers of 2x3 scintillator+PMT
  - ~ 1% prototype of full milliQan detector
- Scintillator slabs and lead bricks
  - Tag thru-going particles, shield radiation

MilliQan Demonstrator



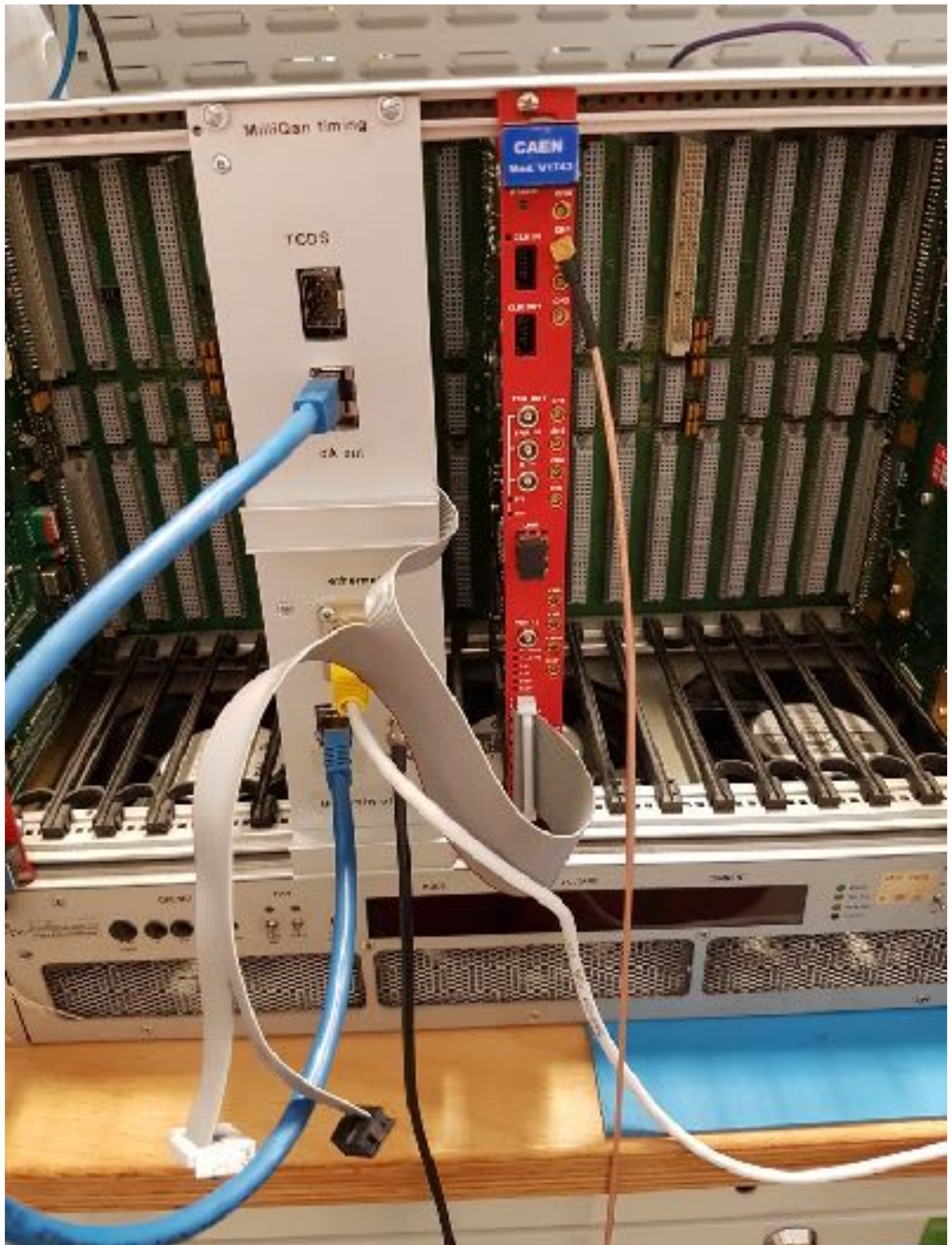
- 3 layers of 2x3 scintillator+PMT
  - ~ 1% prototype of full milliQan detector
- Scintillator slabs and lead bricks
  - Tag thru-going particles, shield radiation
- Scintillator panels to cover top + sides
  - Tag/reject cosmic muons

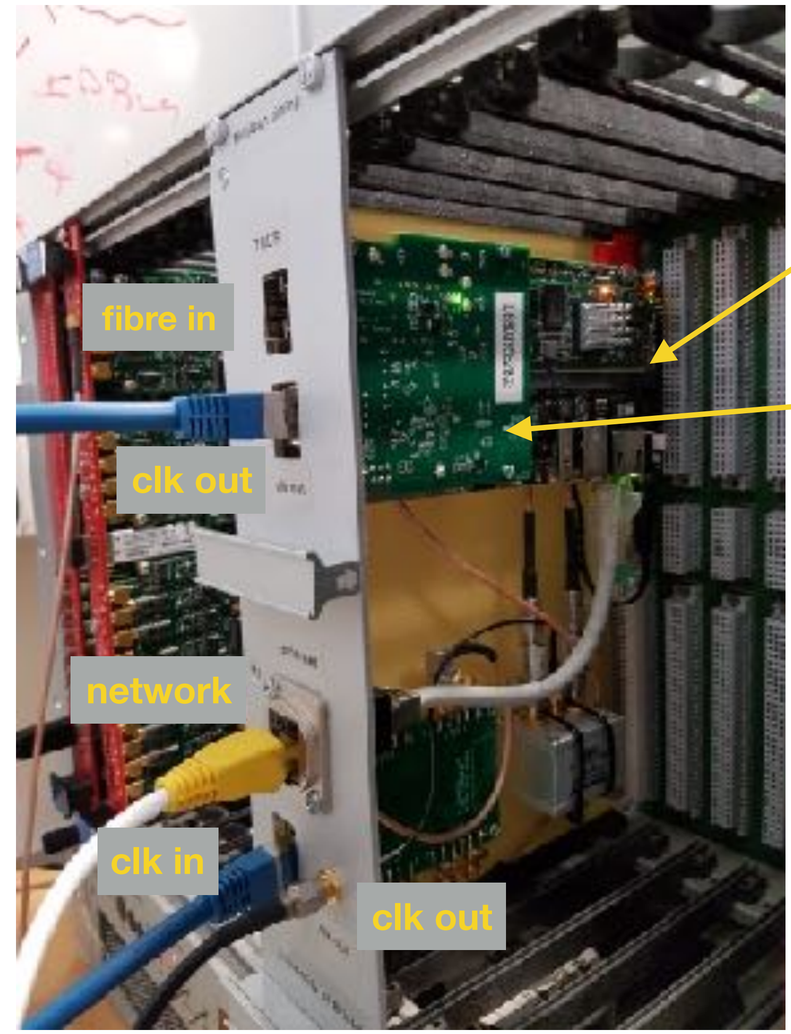
MilliQan Demonstrator



- 3 layers of 2x3 scintillator+PMT
  - ~ 1% prototype of full milliQan detector
- Scintillator slabs and lead bricks
  - Tag thru-going particles, shield radiation
- Scintillator panels to cover top + sides
  - Tag/reject cosmic muons
- Hodoscope packs
  - Track beam/cosmic muons

Readout, Trigger & Timing

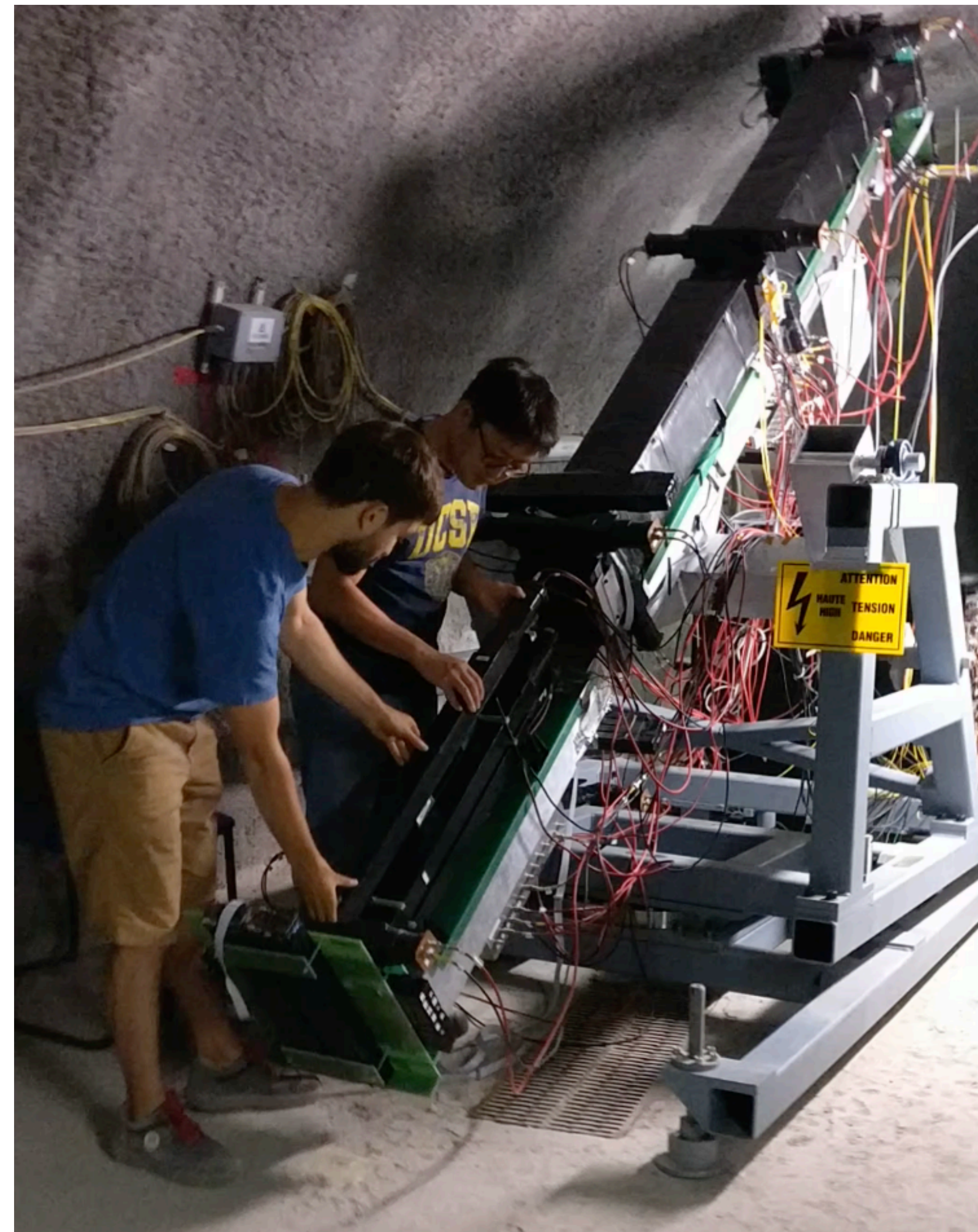




- Scintillator readout & trigger via two CAEN V1743 digitisers
- Hodoscope readout via Arduino
- LHC clock + timing signals received from CMS via card designed for protoDUNE

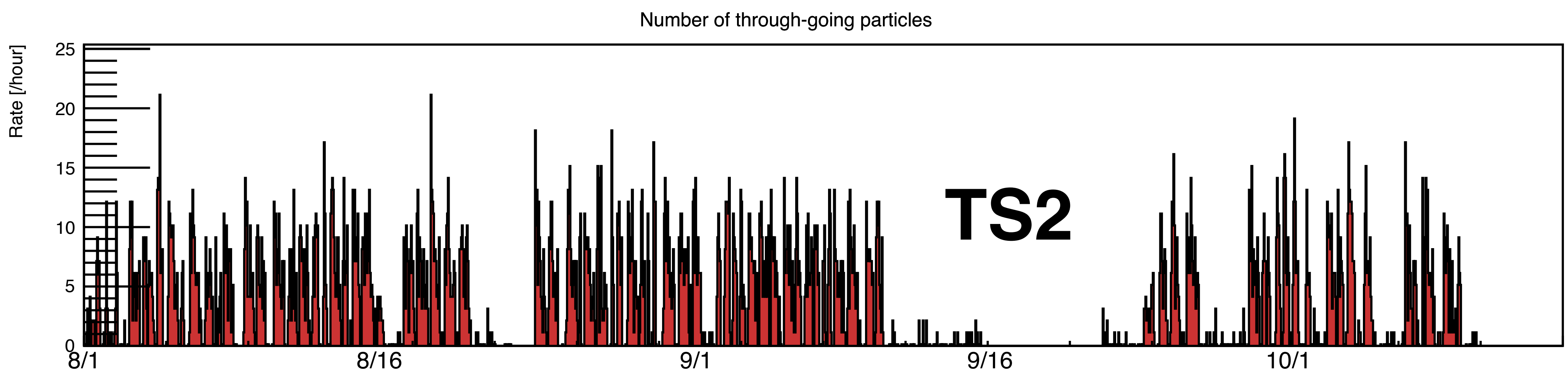
MilliQan Demonstrator

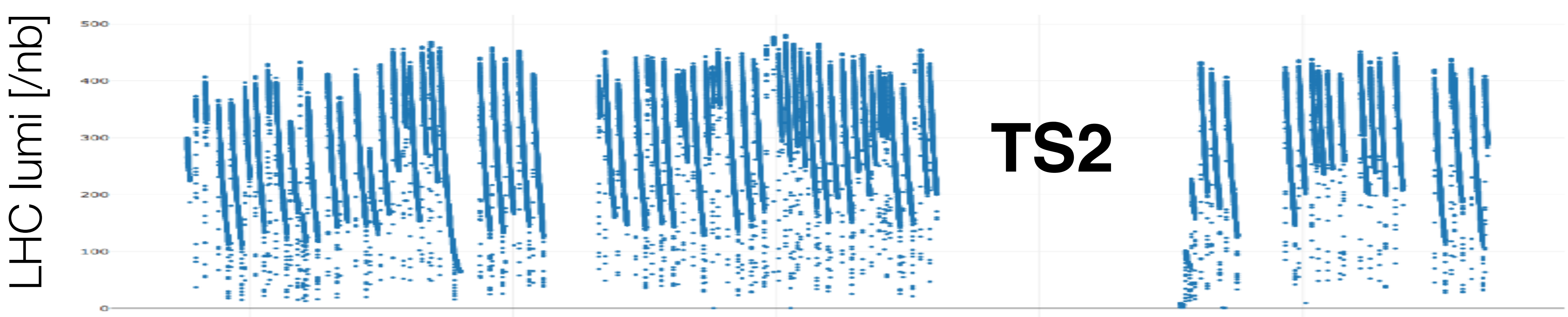
- Demonstrator installed in Sept 2017
  - 2 x 2 x 3 bars
- Upgraded in April 2018
  - 2 x 3 x 3 bars + veto panels/slabs
- Aligned with IP using detailed survey performed by CERN groups
- Operated for ~2000 h during 2018
- Collected ~37 /fb collision data



Demonstrator Results

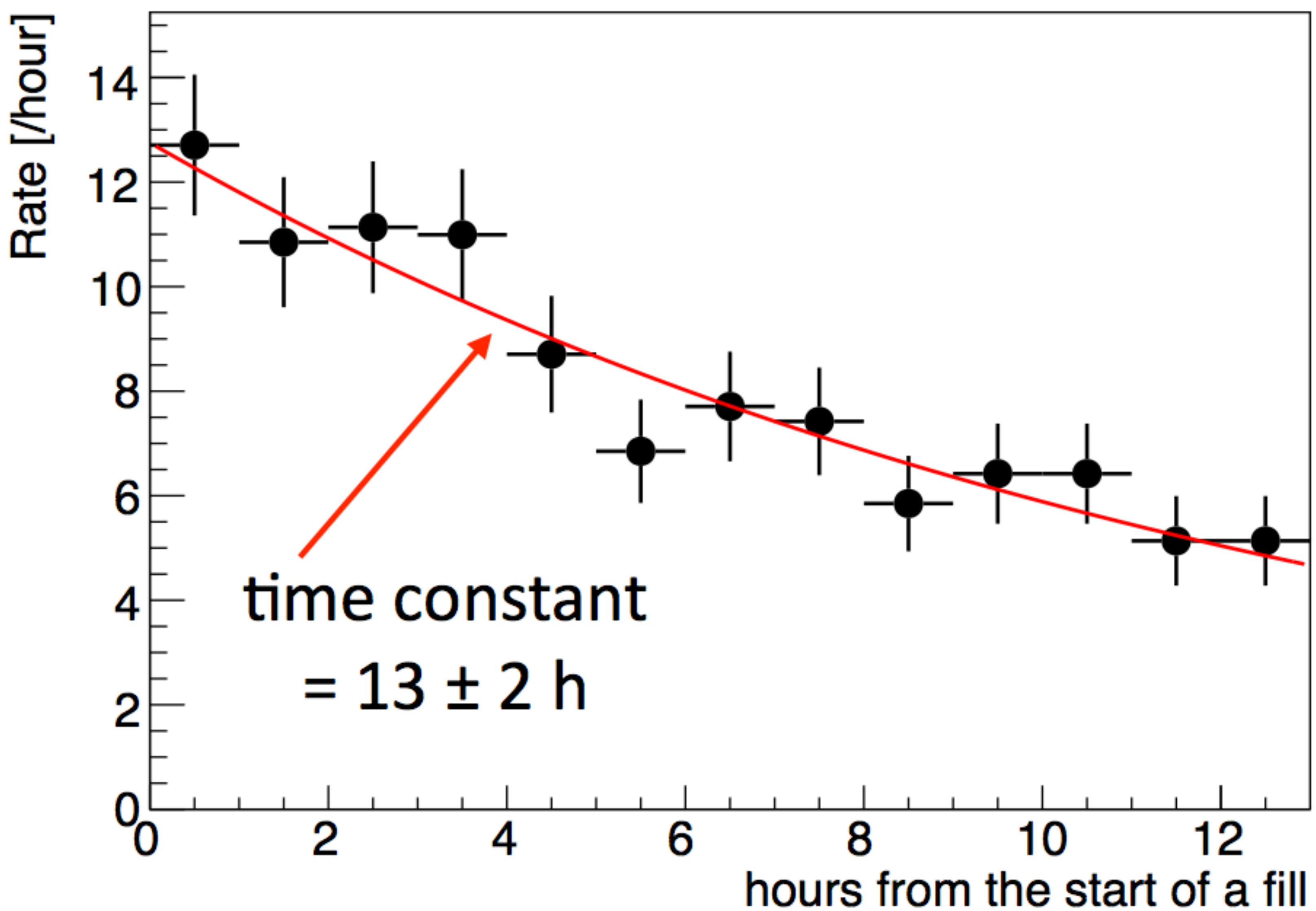
- Can we see LHC collisions and align with the beam ?
- Plot rate of events in all 4 slabs





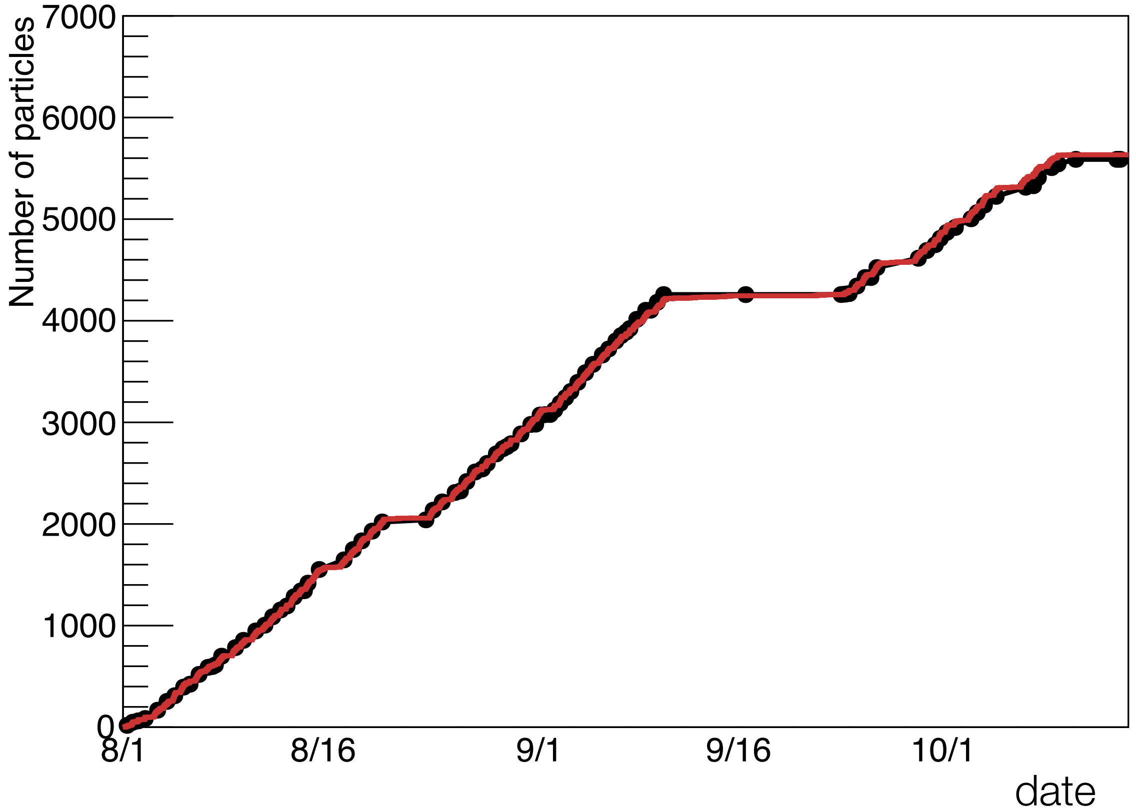
Demonstrator Results

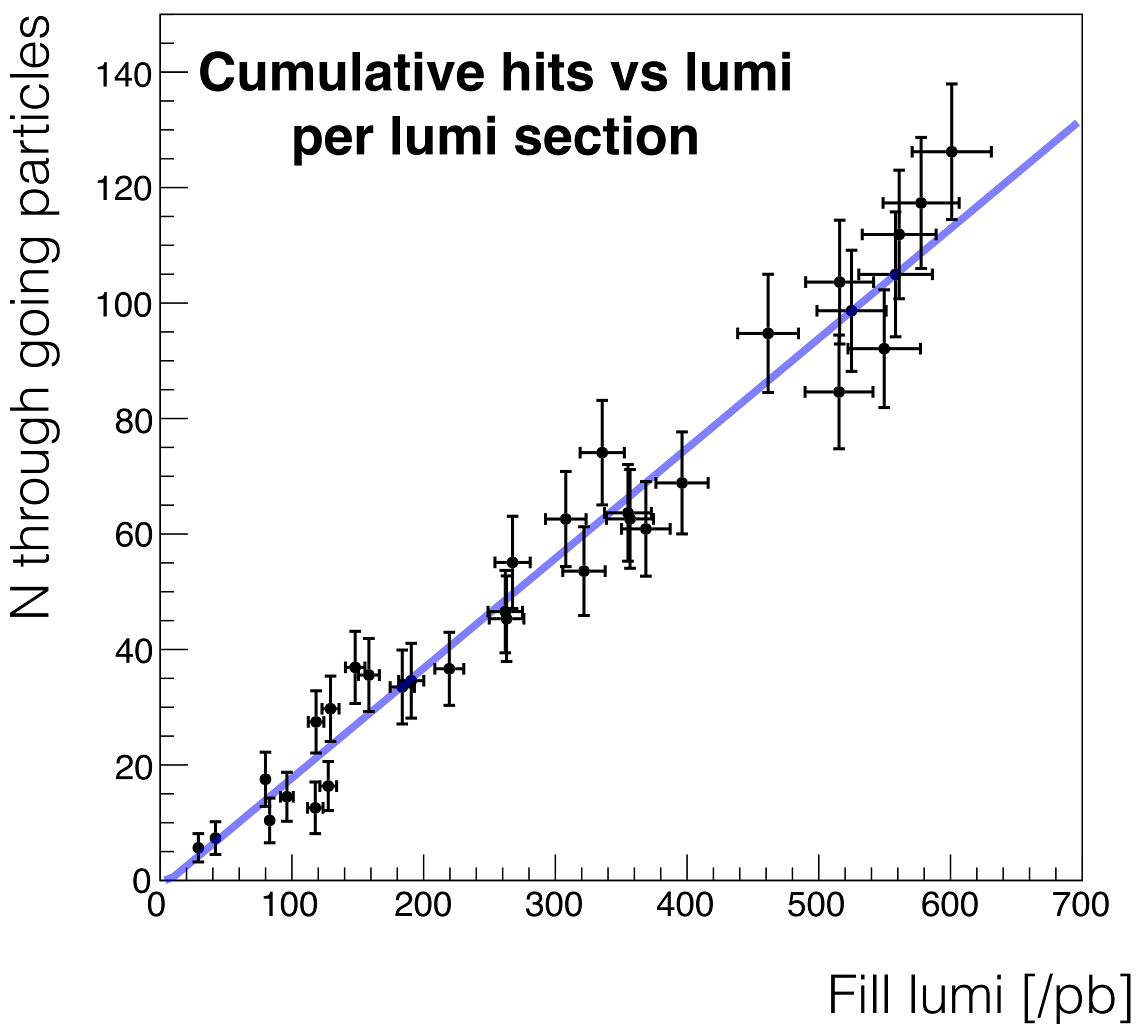
- Can also look at the rate of through-going particles during a fill and compare with the luminosity time constant (14 h in this case)



Demonstrator Results

Black points - total # particles observed
Red line - integrated LHC luminosity

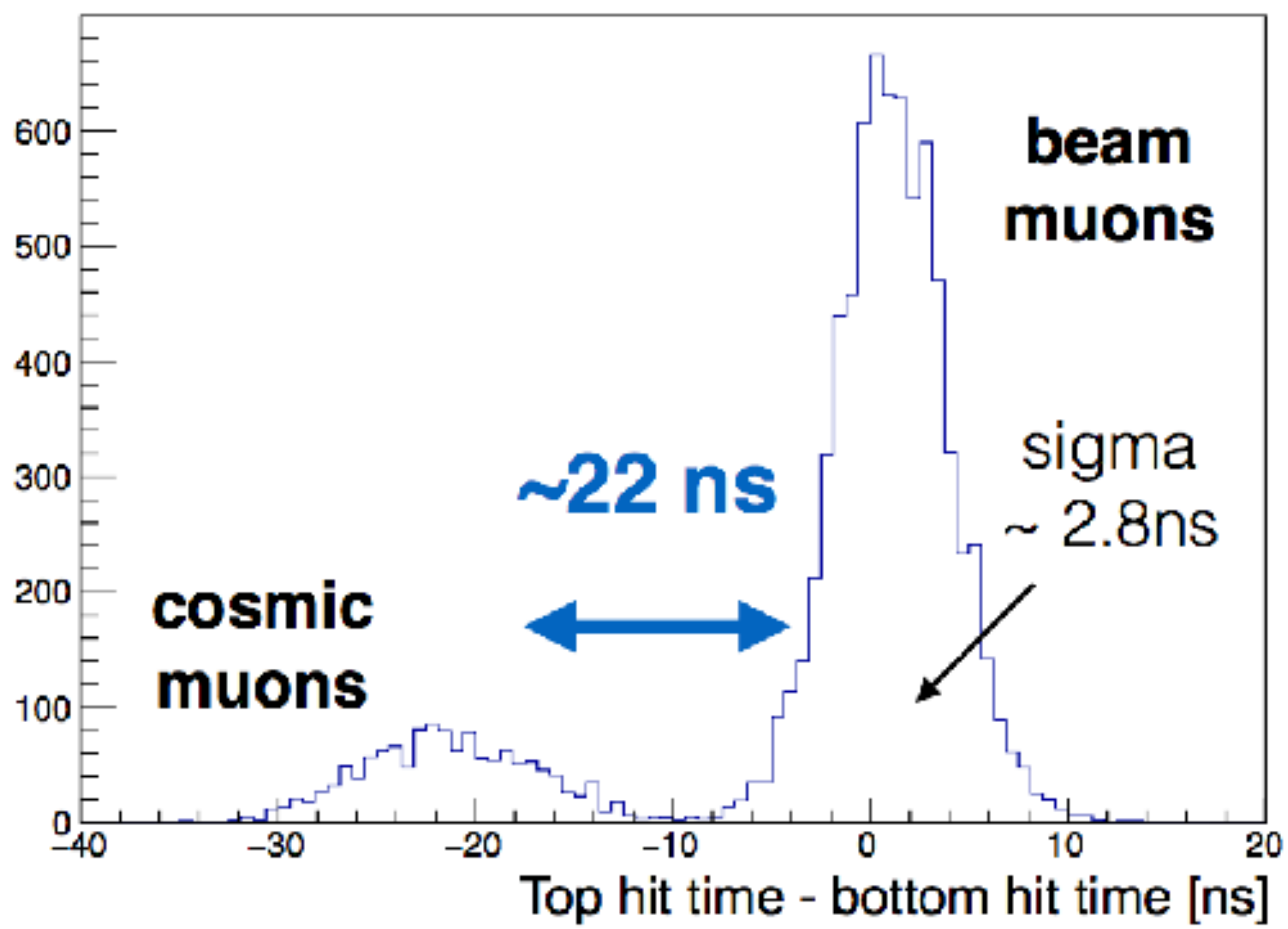




Observed rate of incident particles = **0.19 pb^{-1}**
Expected from simulation = **0.22 pb^{-1}**

Time Precision

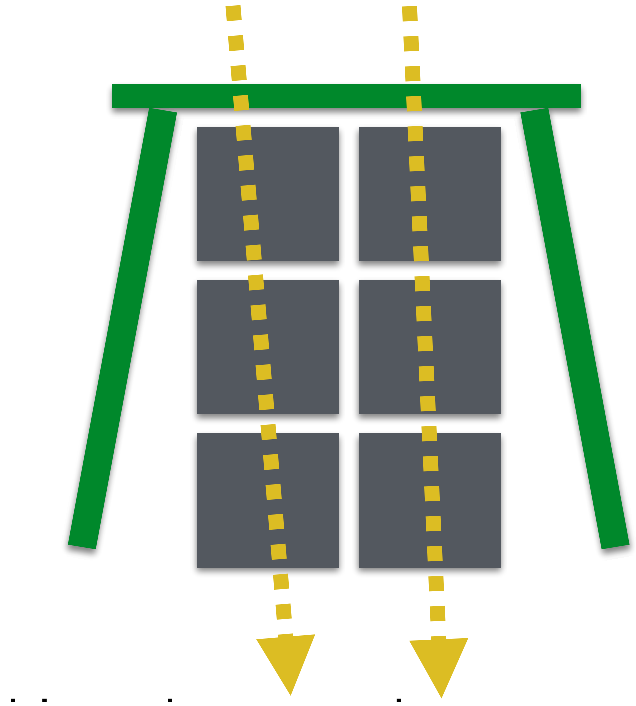
- Background reduction depends on triple-incidence in a small time window
- Need O(few ns) time resolution to achieve desired background rate
- Can test this using through-going particles

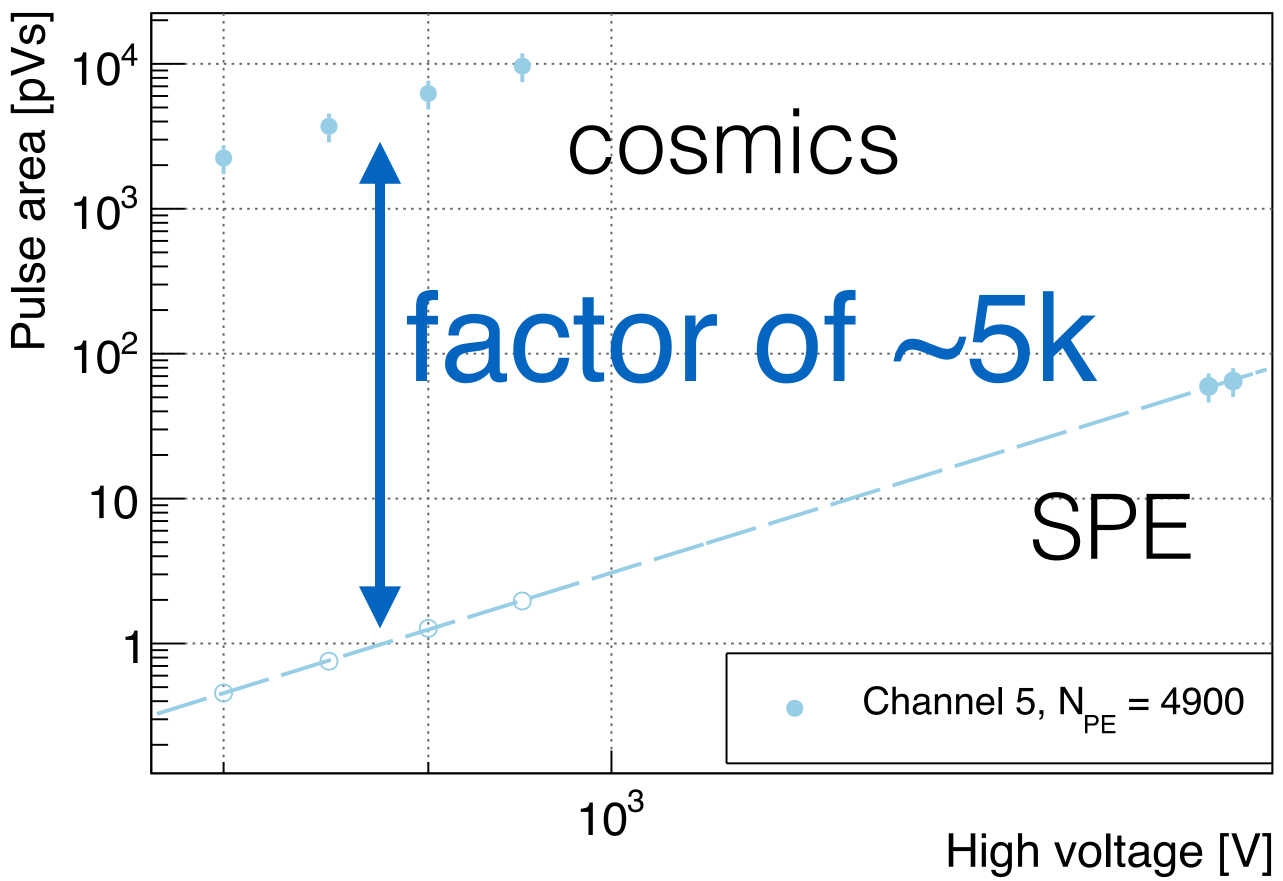


Detector is 3.6m long
Expect **Δt = 2×3.6/c = 24ns**

In-Situ Calibration

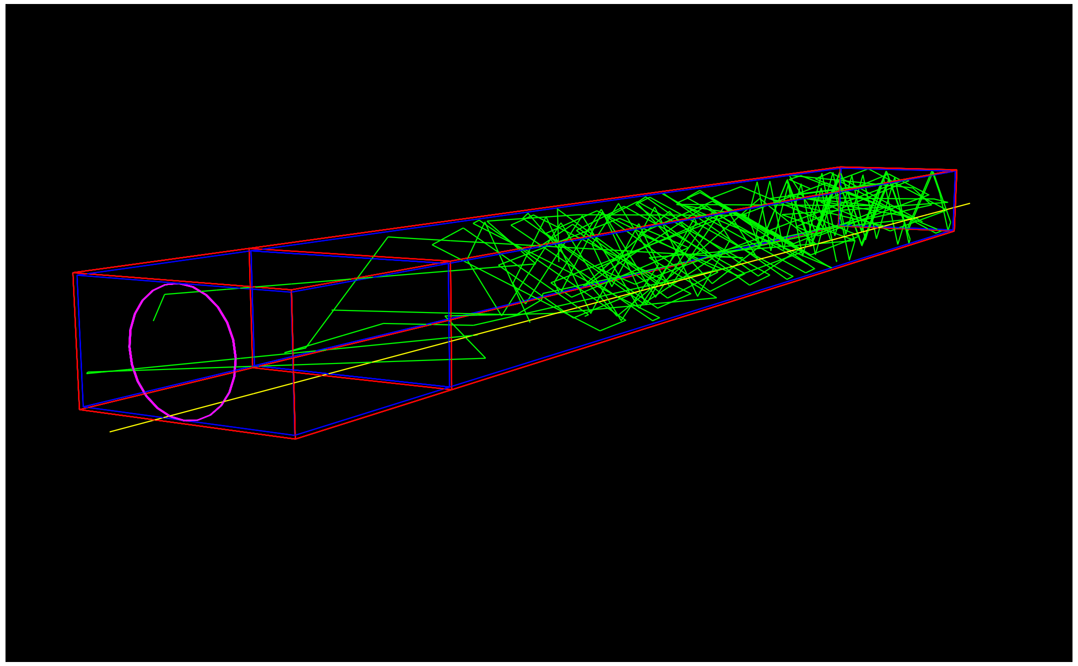
- Mean number of photoelectrons in a bar scales as $N_{PE} = \frac{Q^2}{\xi}$
- Perform charge calibration in-situ using cosmics & SPE (afterpulsing)
- Use down-going cosmics to avoid saturation, and find <N_{PE}> ~ 5k

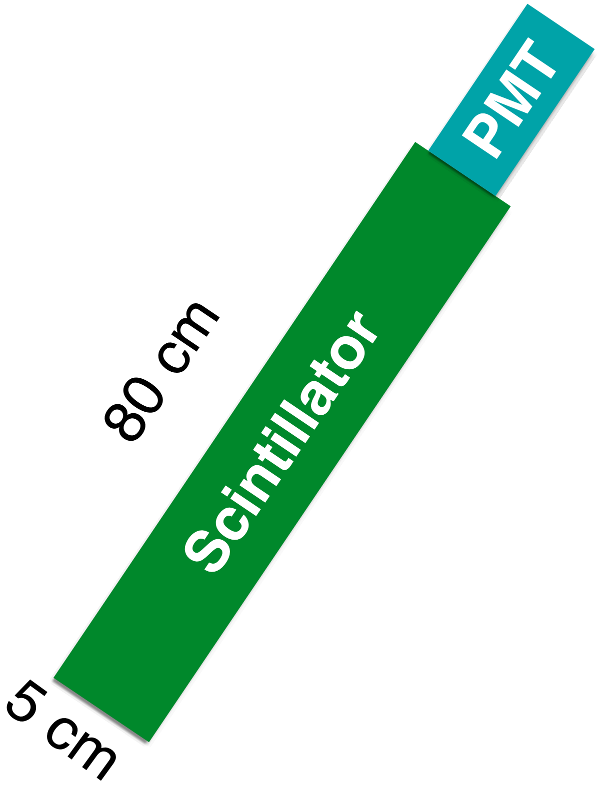




In-Situ Calibration

- Down-going cosmic gives **$\langle N_{PE} \rangle$ ~ 5k**
- Scale by the dimensions of the bar to get through-going cosmic **$\langle N_{PE} \rangle$ ~ 80k**
- Scale by q^2 to find :
  - **$\langle N_{PE} \rangle$=1** for **q = 0.003e**
  - **Consistent with the GEANT4 simulation !**

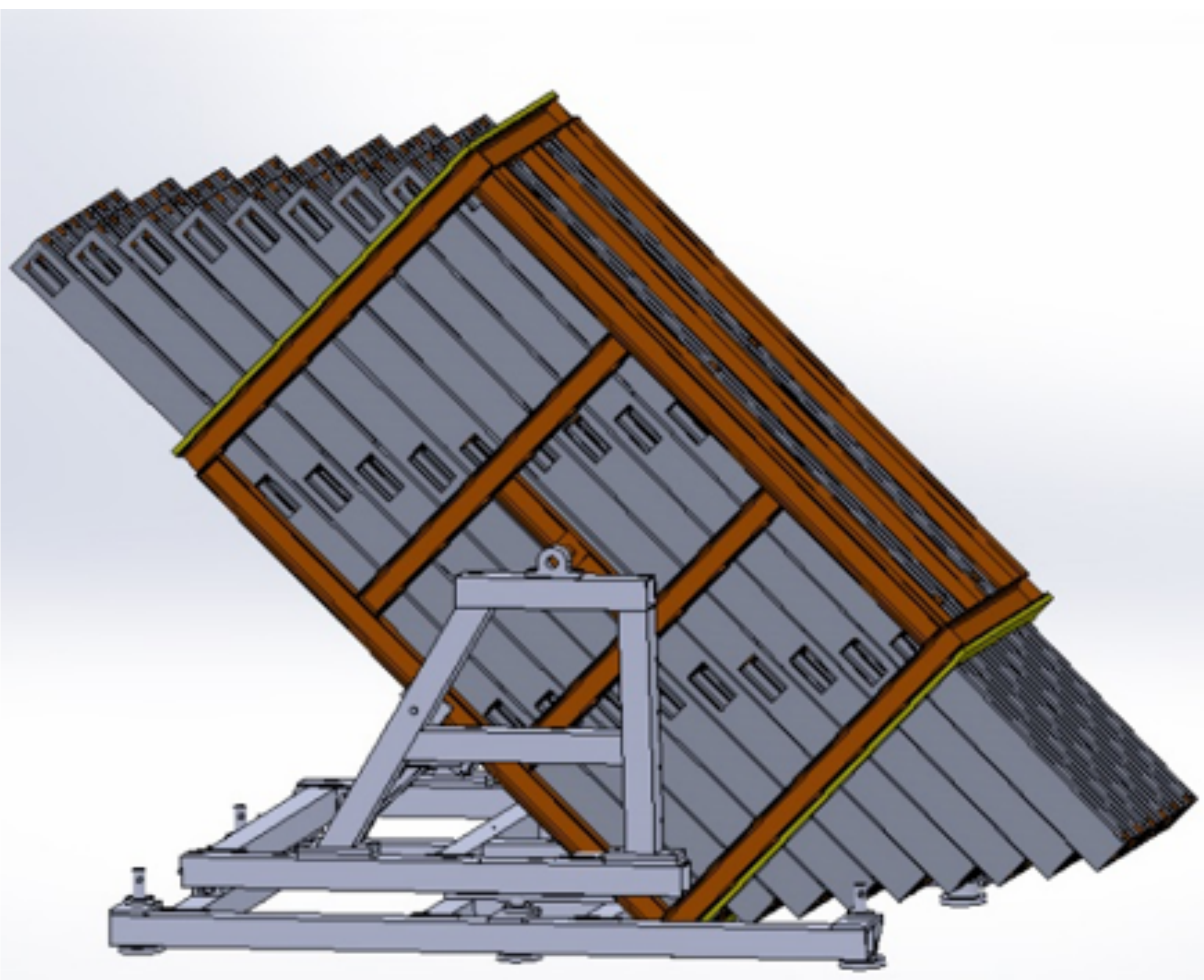


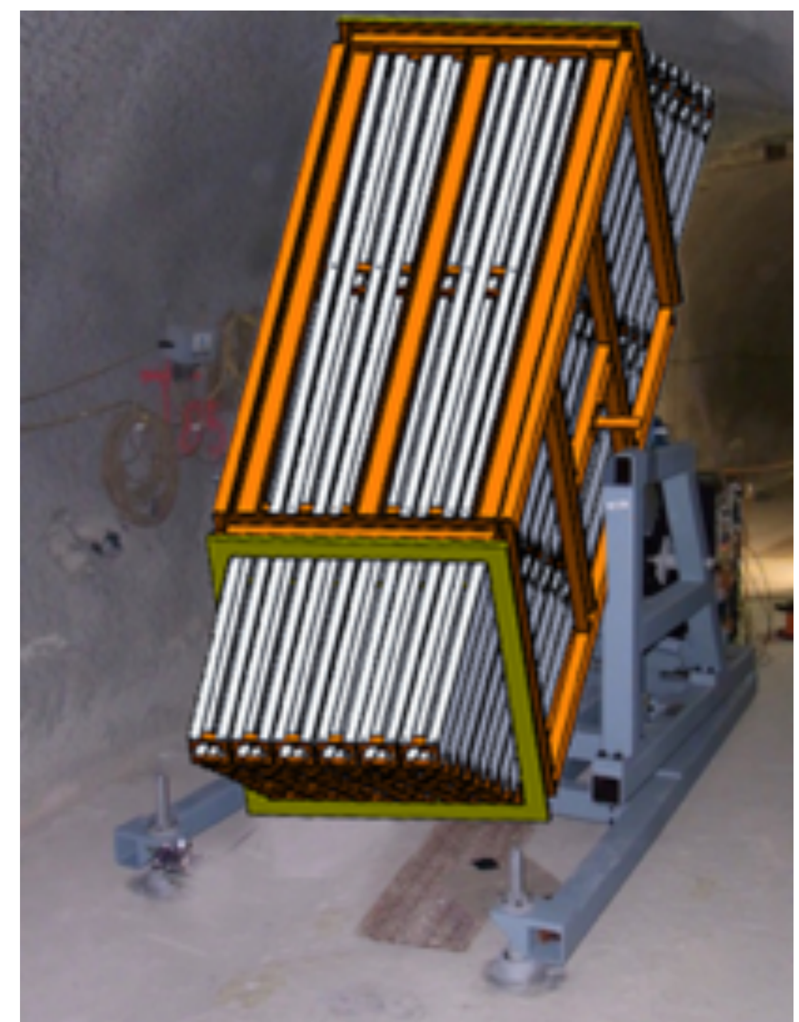


Thanks to these guys

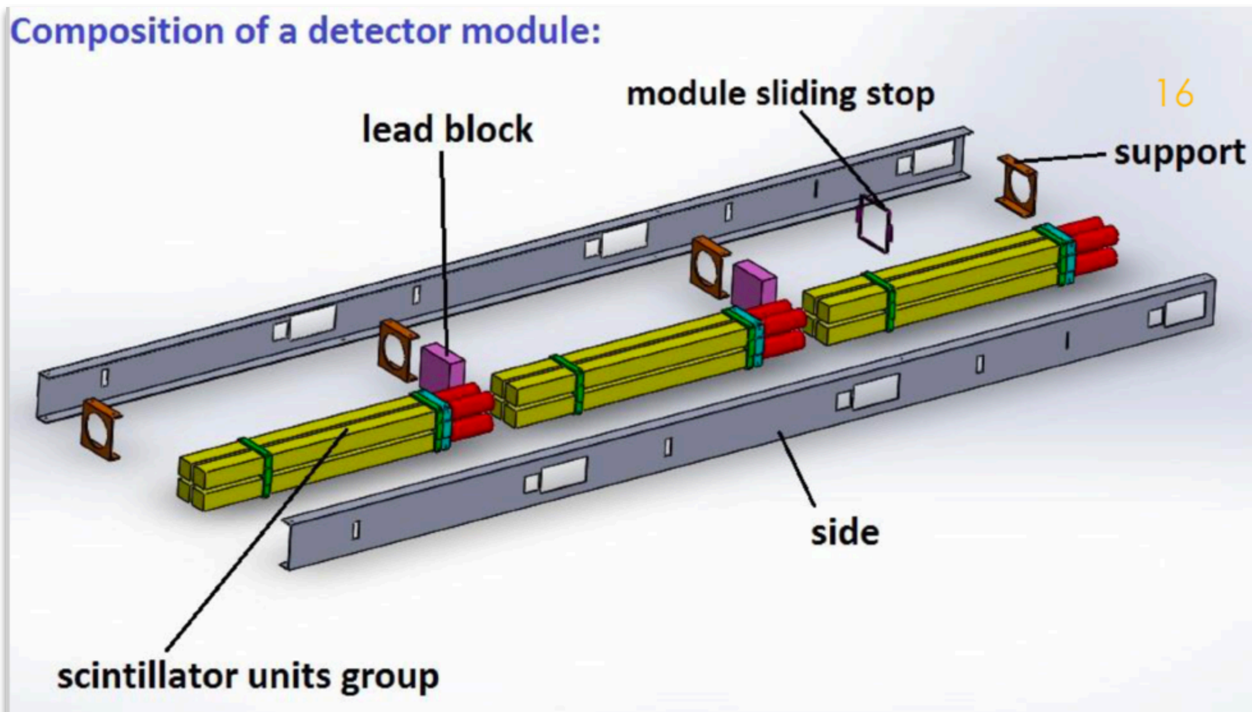
Updated Design

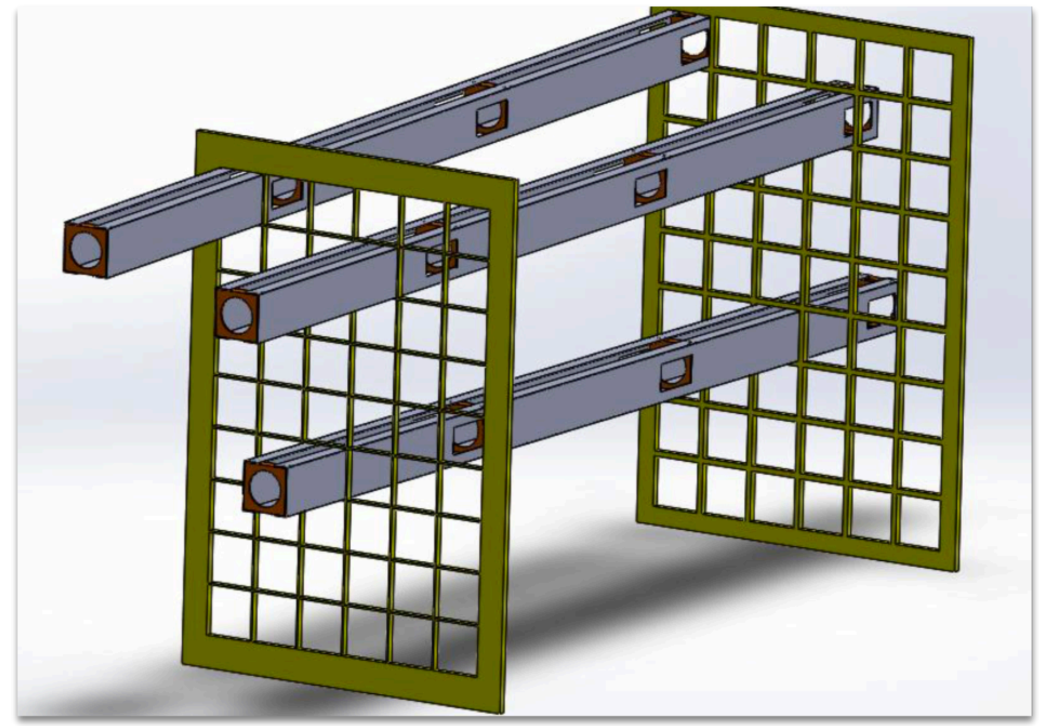
- Original design comprised 3 layers of scintillator bars + PMTs
- “Stepped” geometry allows bars to be longer within same cavern space
  - And allows us to install more than one array in PX56





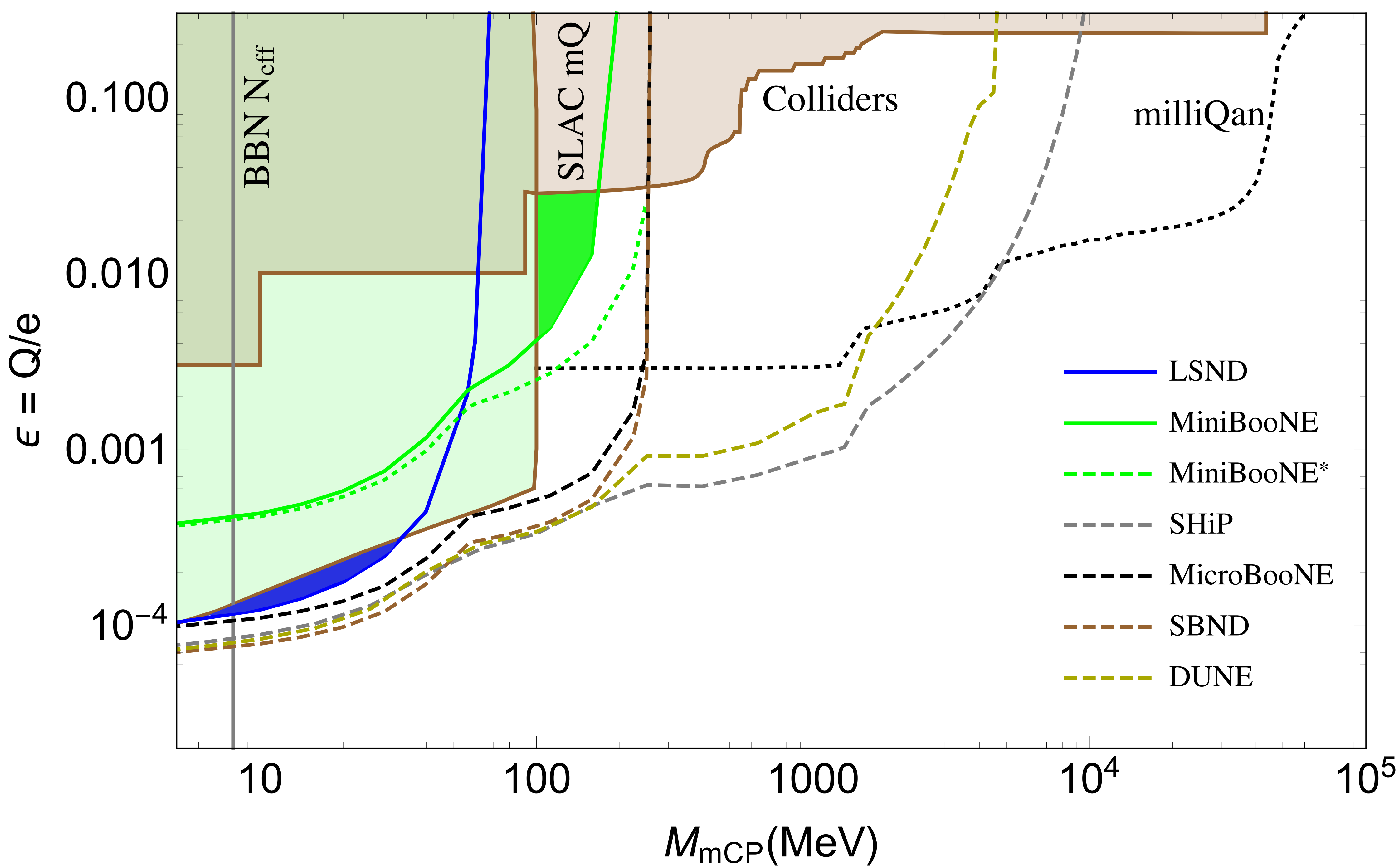
Updated Design





- Detailed designs of mechanical assembly now at an advanced stage
- Modular design allows components to be carried through the 1.2m x 2m door into the tunnel
- Ongoing work on LV-to-HV power supplies & trigger electronics

Beyond Colliders…



arXiv:1806.03310

Summary

- **Ionisation energy loss** is a interesting way to look for new physics
  - It could give insights into quantisation of charge!
- Highly ionising monopoles, or ***lowly-ionising millicharges***
- **MilliQan** is a simple, low cost, detector that could shed light on unexplored regions of the millicharge/mass plane
  - Letter of Intent : arXiv:1607.04669
  - **~ $900k per detector array**
- Successful demonstrator, now we just need to scale it up to give useful sensitivity….

Backup

Efficiency Estimation

- Probability to observe 1 or more photoelectrons in each of 3 layers :

$$P = (1 - e^{N_{PE}})^3$$

- Where average number of photoelectrons is given by $N_{PE} = \frac{Q^2}{\xi}$

- Constant of proportionality estimated from scintillator light yield, detector dimensions, 10% detection efficiency, typical energy deposit of MIP ~ 0.0024

- Compares well with GEANT4 simulation !