milliQan: search for milli-charged particles at the LHC

Matthew Citron

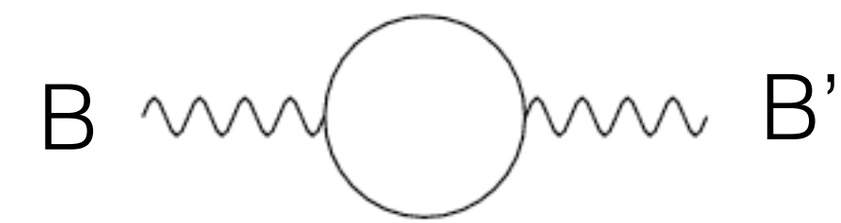
No sign of new physics at the LHC

What could we be missing? Look to dark matter - many SM extensions include a **dark or hidden sector**

Why milli-charged?

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

kinetic mixing



SM

dark sector

massless U'(1) boson in the dark sector

'dark EM'

$\kappa \sim 10^{-3} - 10^{-2}$

(naturally $\sim \alpha/\pi$)

Kinetic mixing with a new massless 'dark' boson **can provide link between SM and a hidden/dark sector**

Why milli-charged?

Now add fermion charged under new U'(1):

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

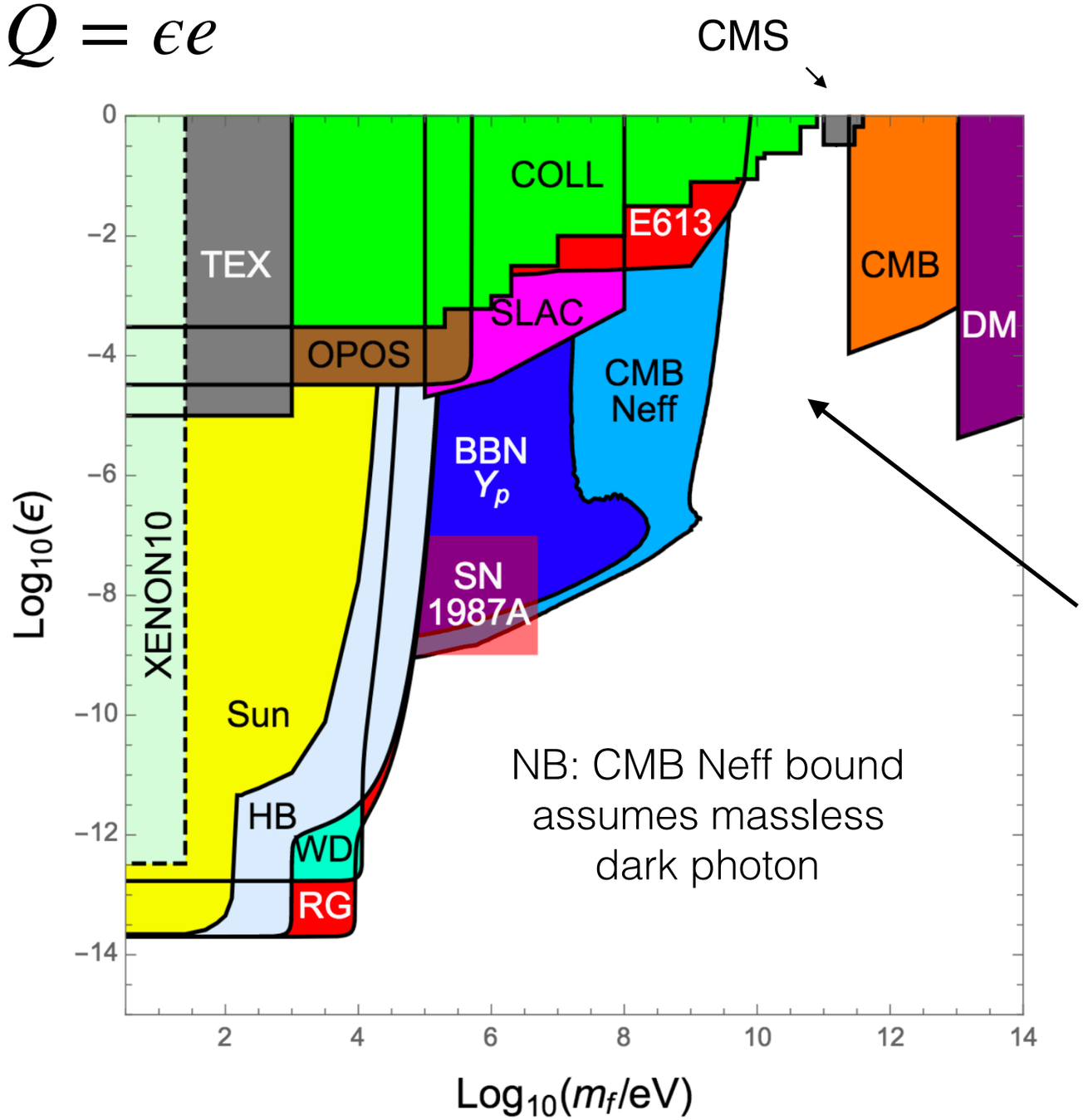
Standard trick - redefine gauge field B': $B' \rightarrow B' + \kappa B$

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

new fermion has small EM charge**: milli-charged particle**

Many ways to search for mCP

$Q = \epsilon e$



Searches using colliders, effects on sun, stars and supernovae, cosmological bounds,… cover wide range in masses/charges

but

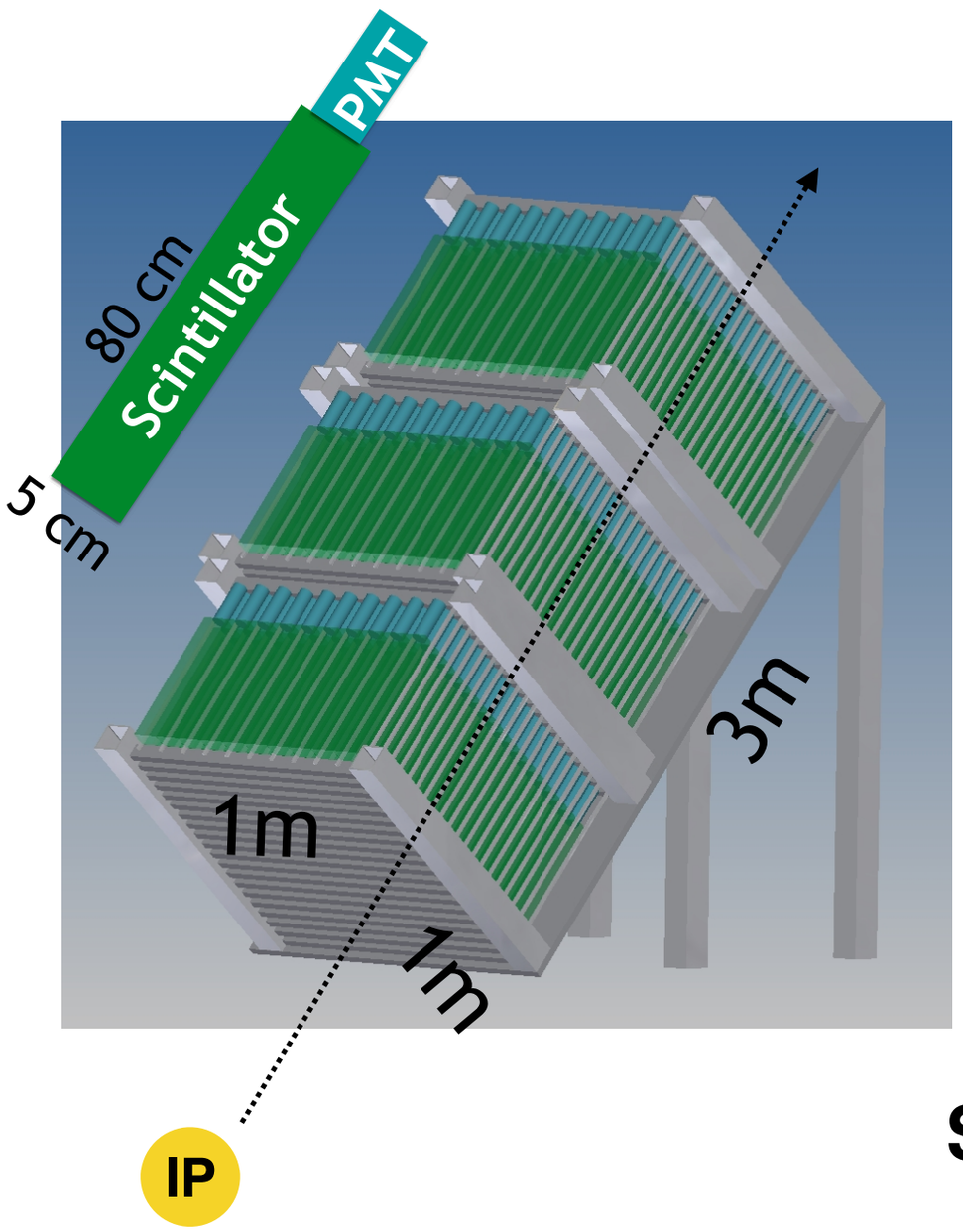
big gap for heavier (~ GeV) low charged particles → requires dedicated experiment

target with **milliQan** at the LHC!

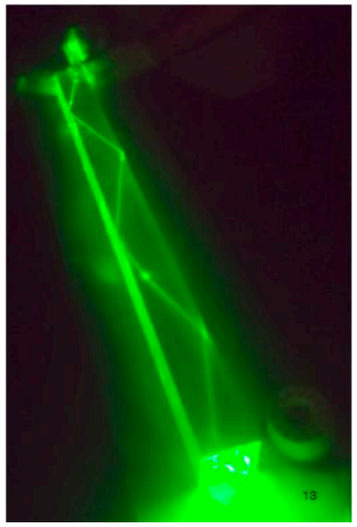
arXiv:1511.01122

milliQan detector concept

Initial design in 2016 LOI: 1200 scintillating bars in three layers (400 pointing paths)



PMT

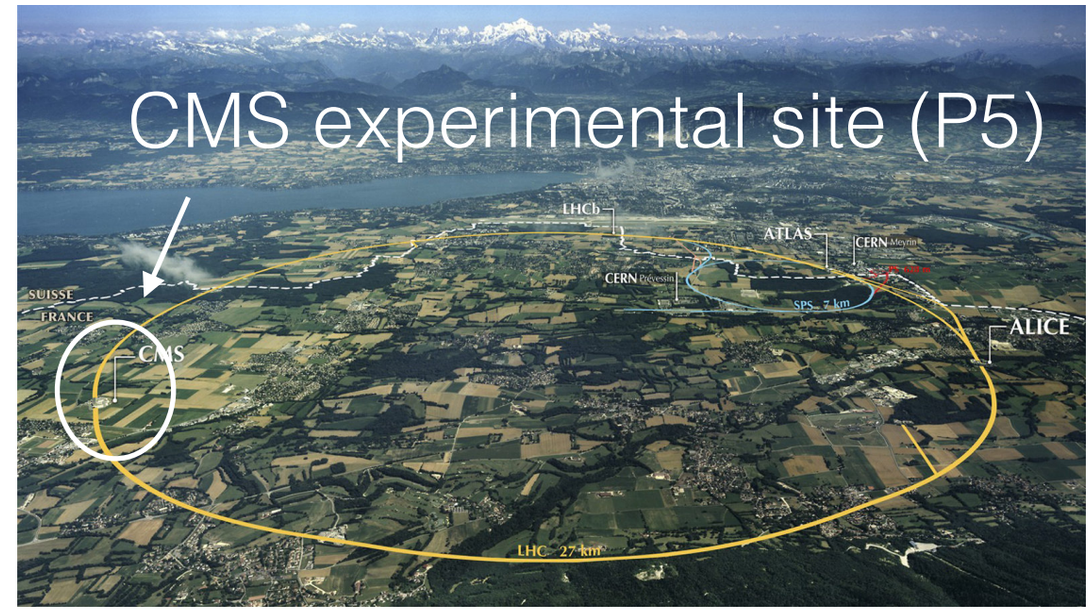


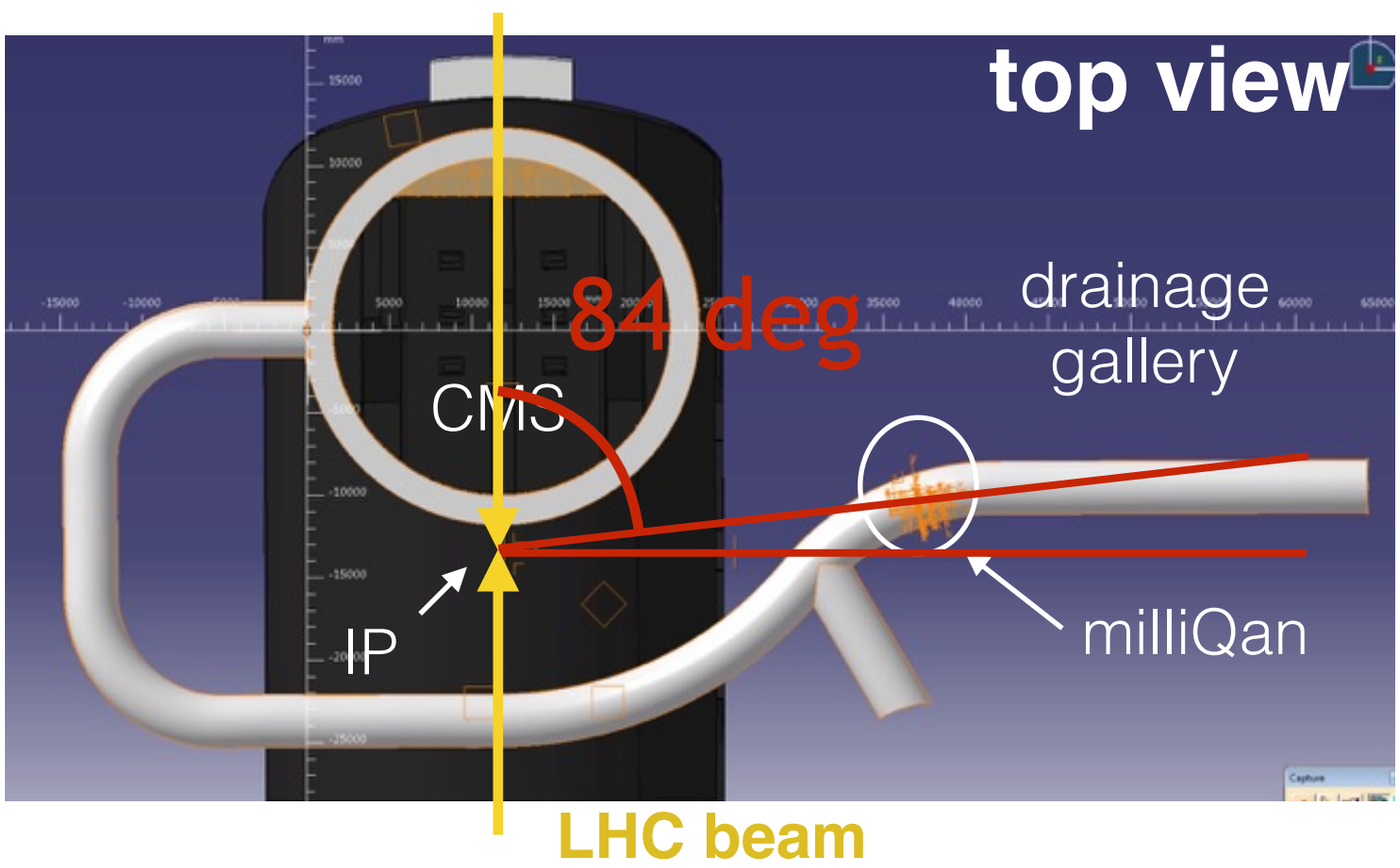
Scintillator bar

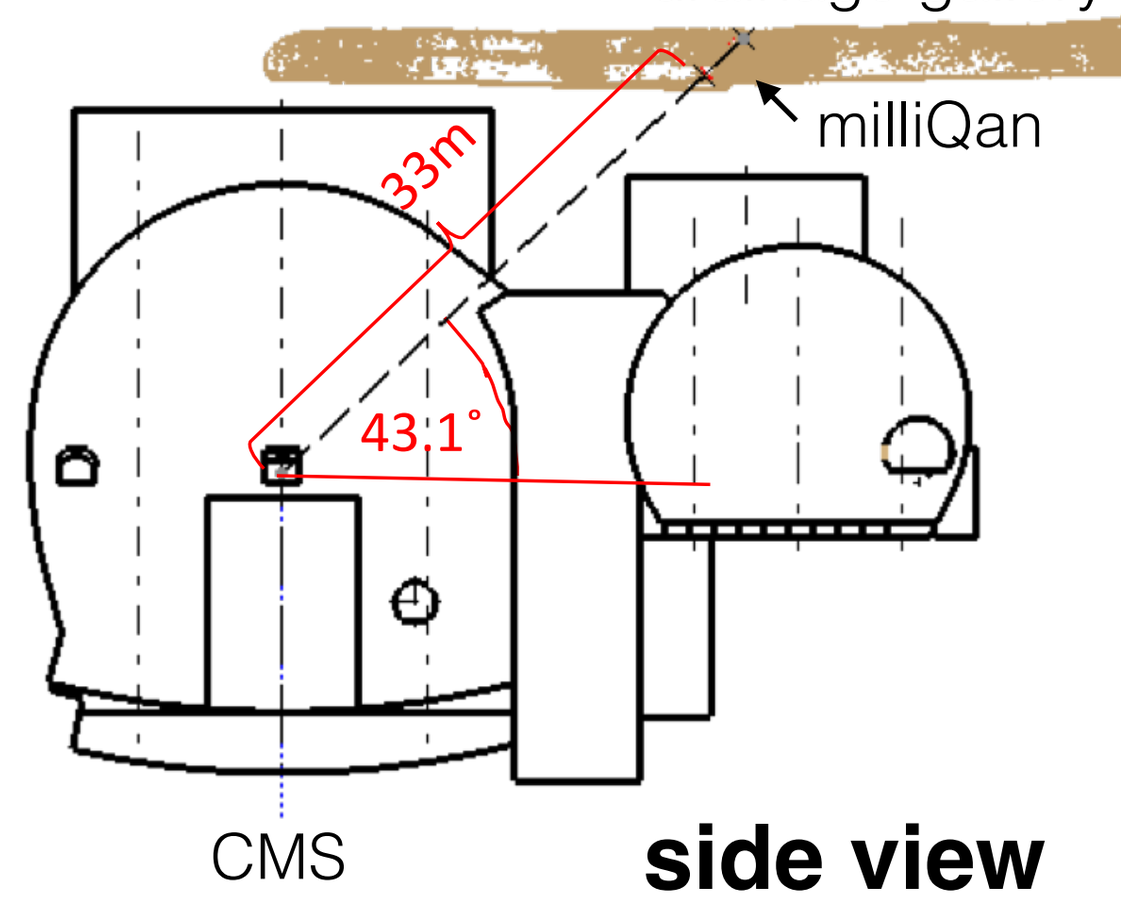
- **Key idea**: use scintillator bar array to detect (very) small ionisation from low charged particles produced by the LHC
- Expected signal: few scintillation photons in all three layers
- Each bar + PMT must be capable of detecting a single scintillation photon
- Control backgrounds: signal in each layer within small time window and which points towards the IP
- Easy to scale and adapt!

Proposed location

- Place detector in CMS experimental site within existing ‘drainage gallery’
- Location 33 m from interaction point (including 17 m rock) → beam particles greatly suppressed





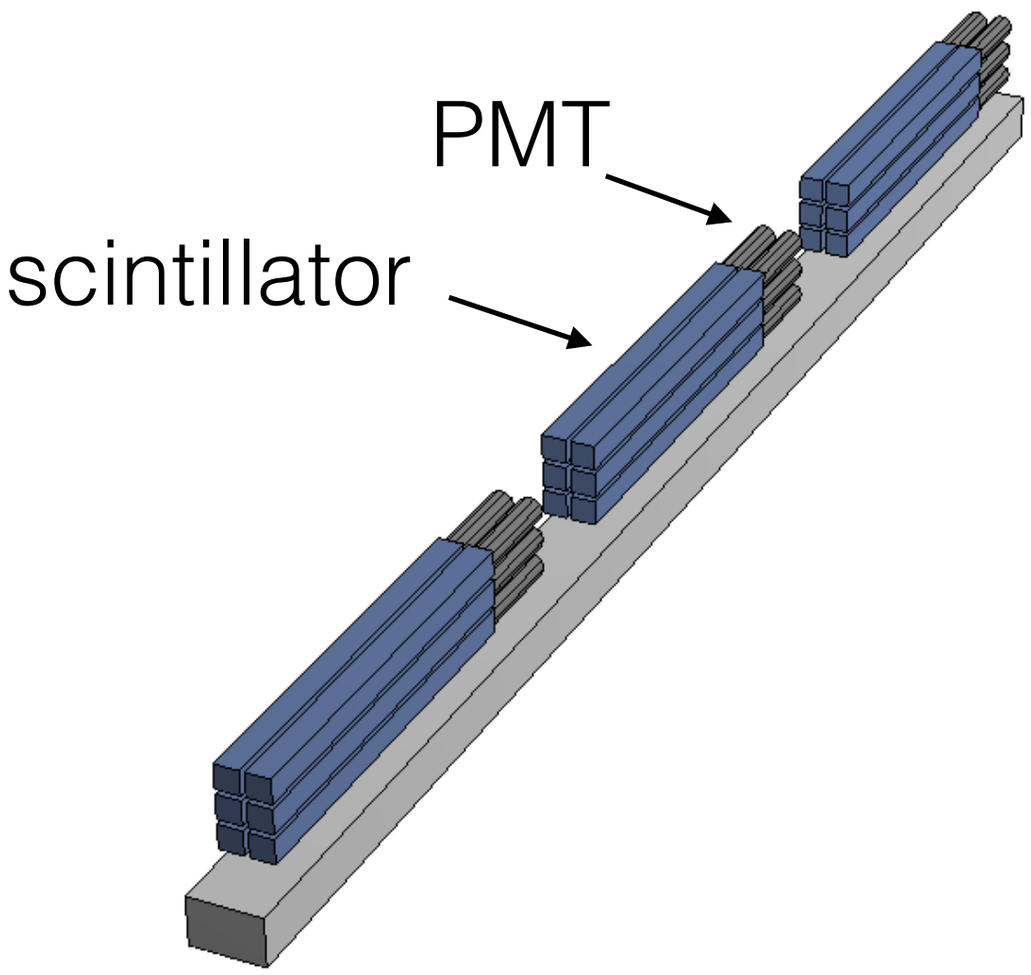


Proposed location

2.78m high
2.73m wide

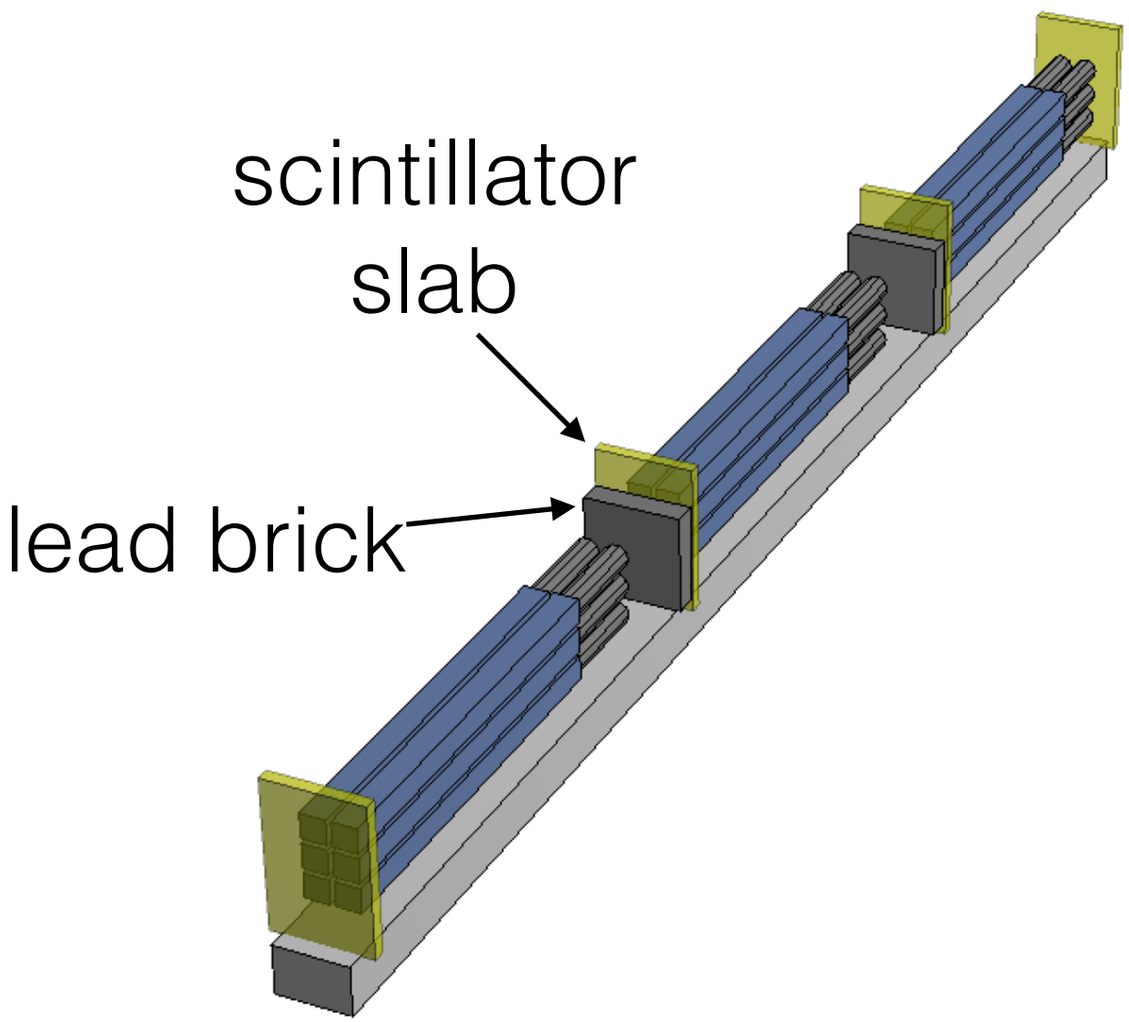
Sept 2017: milliQan demonstrator installed to **study backgrounds** and **prove feasibility** of the experiment!

Demonstrator components



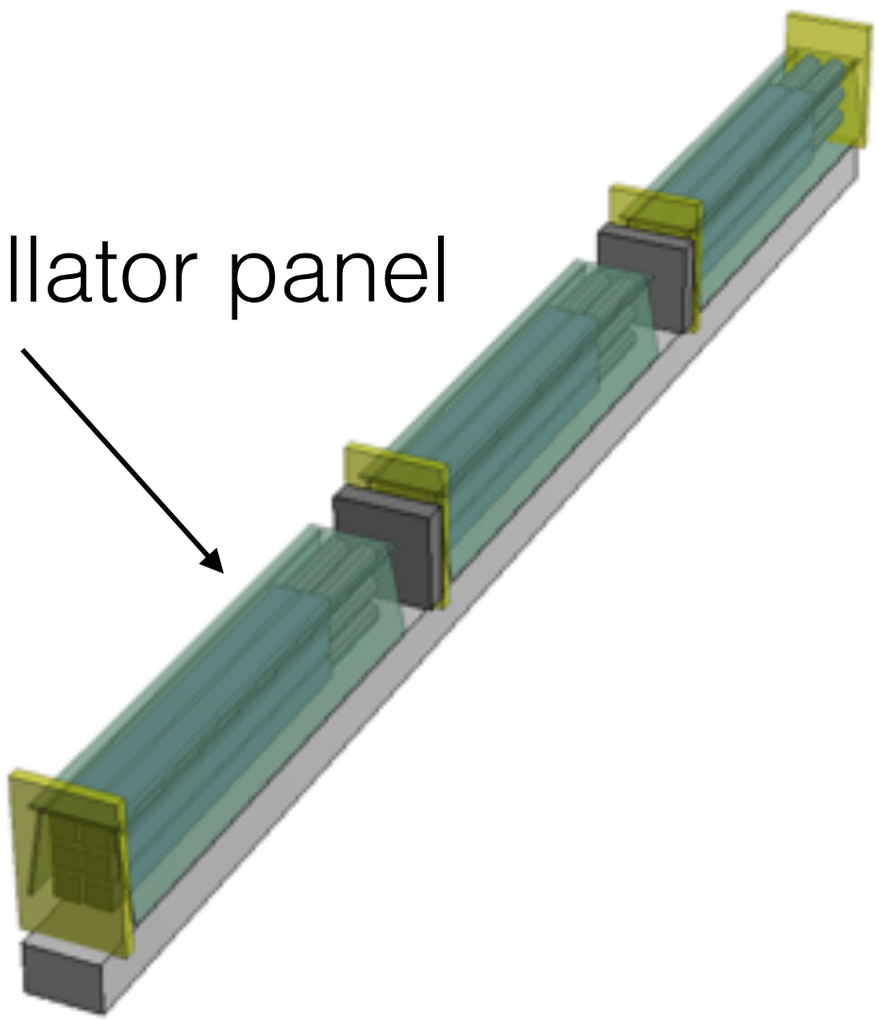
- 3 layers of 2x3 scintillator+PMT
  - ~ 1% prototype of full milliQan detector

Demonstrator components



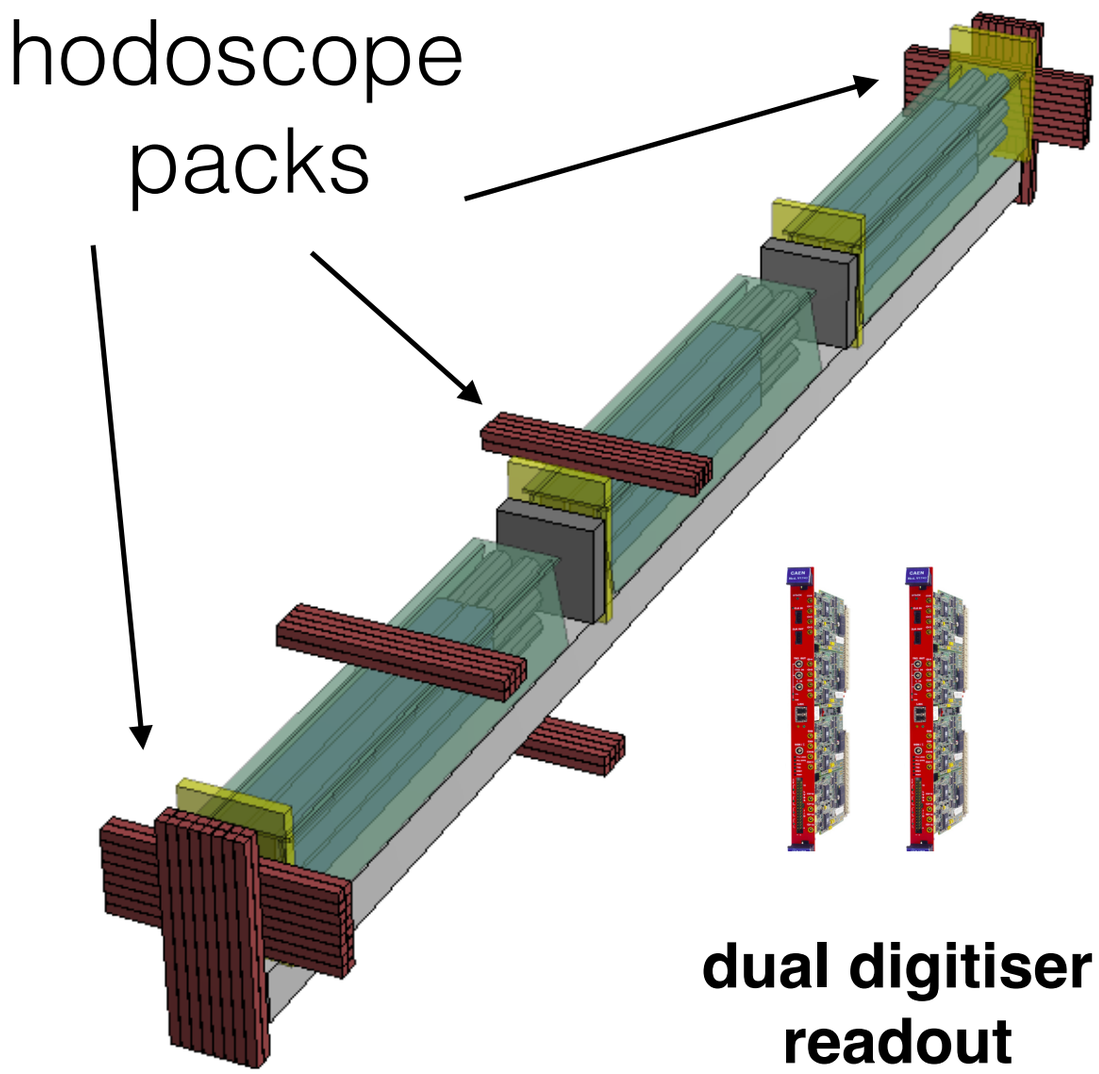
- 3 layers of 2x3 scintillator+PMT
  - ~ 1% prototype of full milliQan detector
- Scintillator slabs and lead bricks
  - Tag thru-going particles, shield radiation

Demonstrator components



- 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 cosmic muons

Demonstrator components

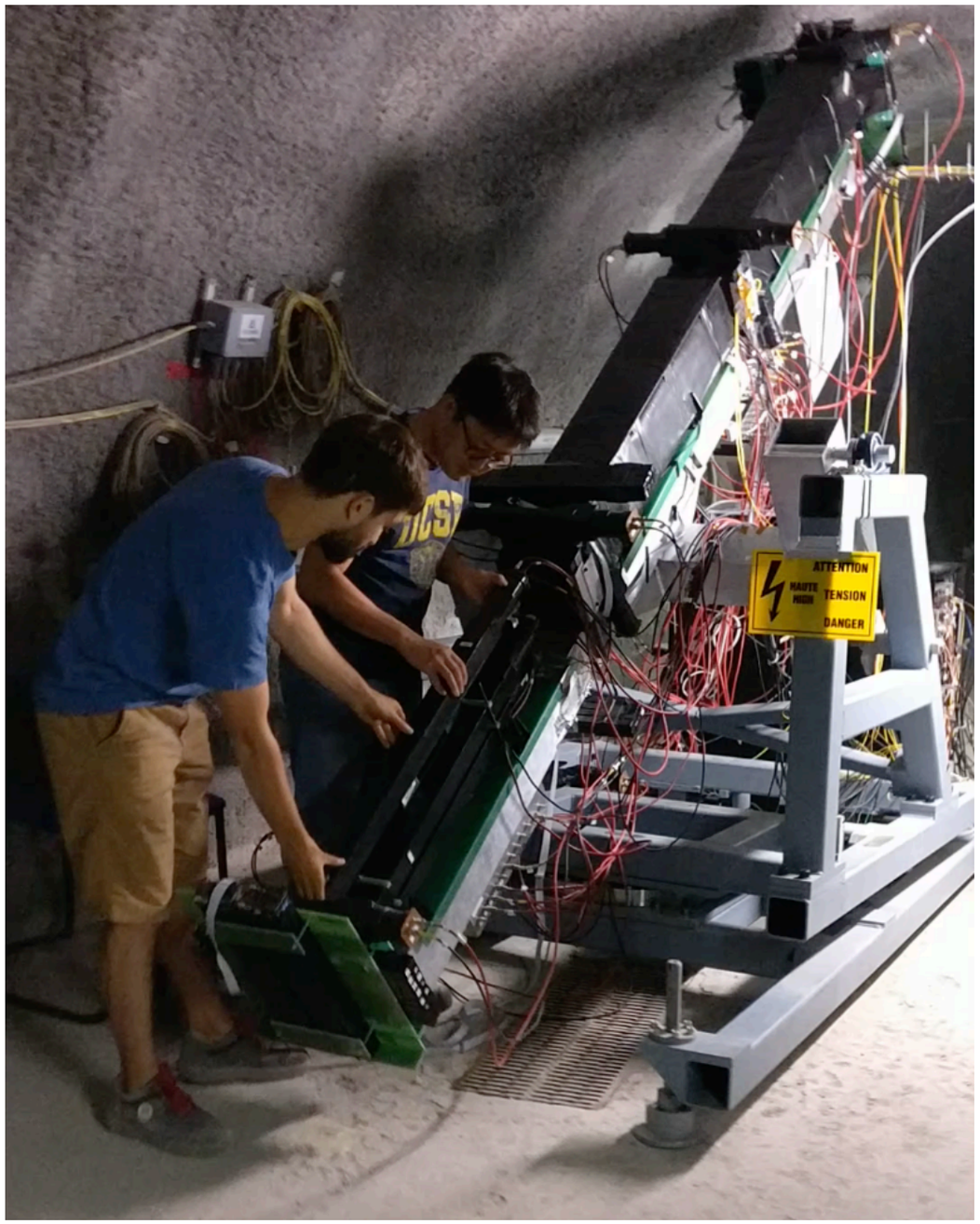


dual digitiser readout

CAEN V1743 digitizer:
16 chan, 1.6 GS/s,
640 ns window

- 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
- Hodoscope packs
  - Track beam/cosmic muons
- Environmental sensors to measure humidity and magnetic field

Demonstrator

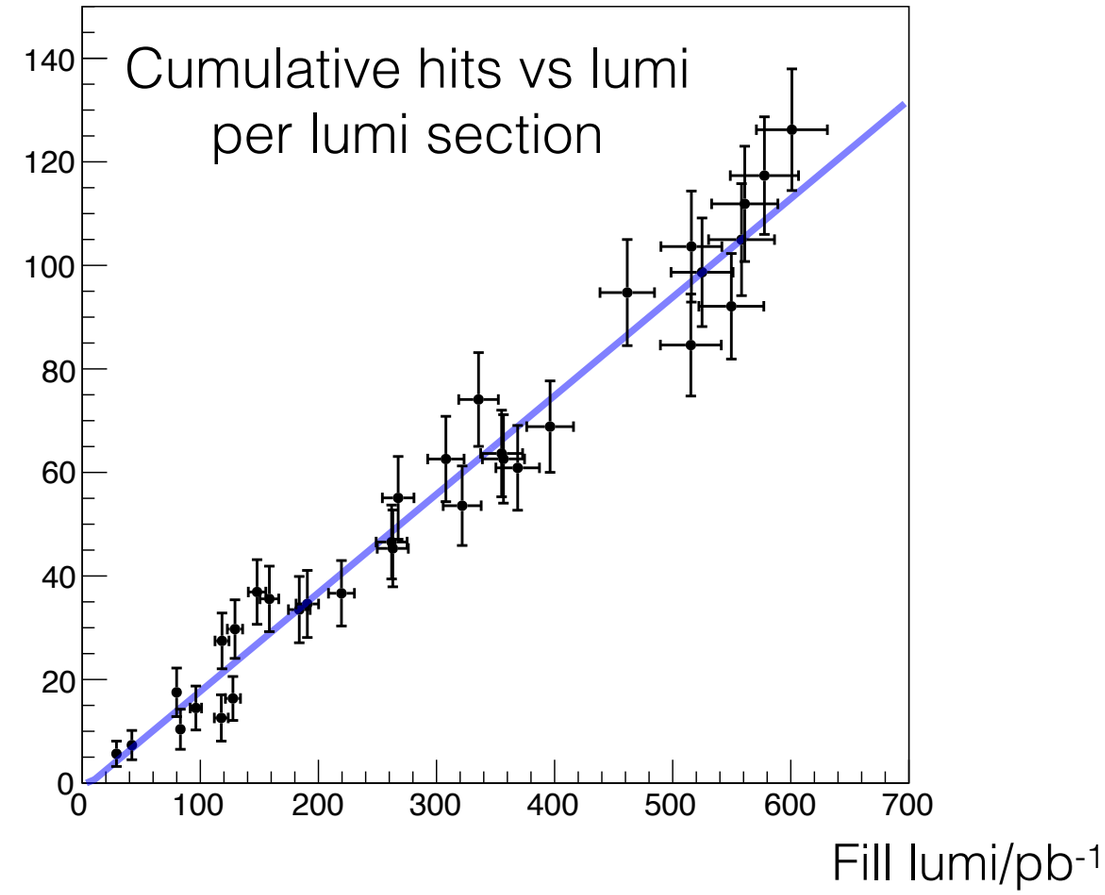


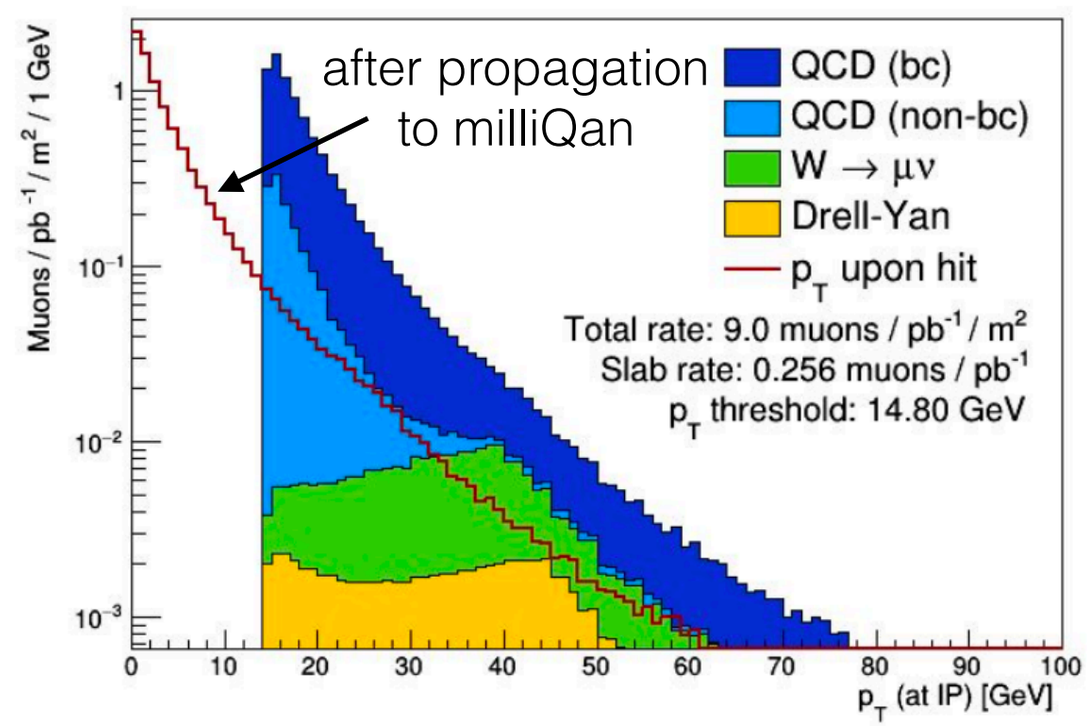
Installed on mount designed to hold full detector

- Ran very successfully, collecting **~35/fb**, **2000h** of data in 2018
- Operational experience in difficult environment: triggering/DAQ/DQM
- Used for range of studies to prove feasibility of full detector
- Key results on next slides: **alignment**, **calibrations**, **background measurements**
- Fully simulated in GEANT4

Alignment

- milliQan 'sees' muons from the CMS interaction point
- Check occupancy agreement with expectation
  - Simulate production at CMS interaction point
  - Propagate through CMS material and 17 m of rock considering **multiple scattering** and **CMS magnetic field**
- Expected rate: **0.28± 0.09/pb^{-1}**
- Measured rate: **0.19/pb^{-1}**

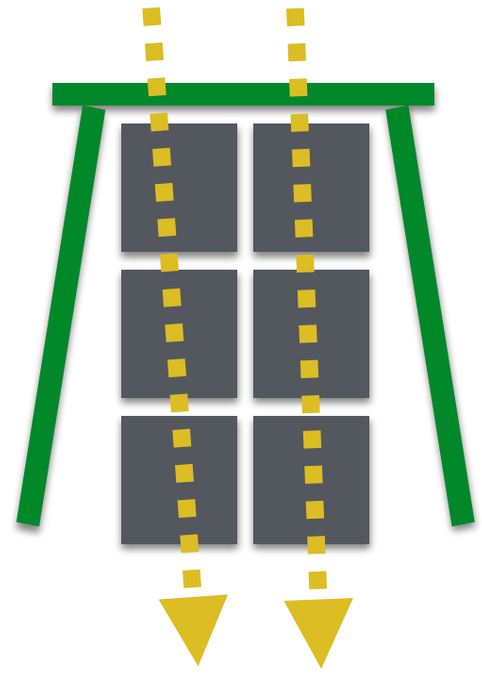




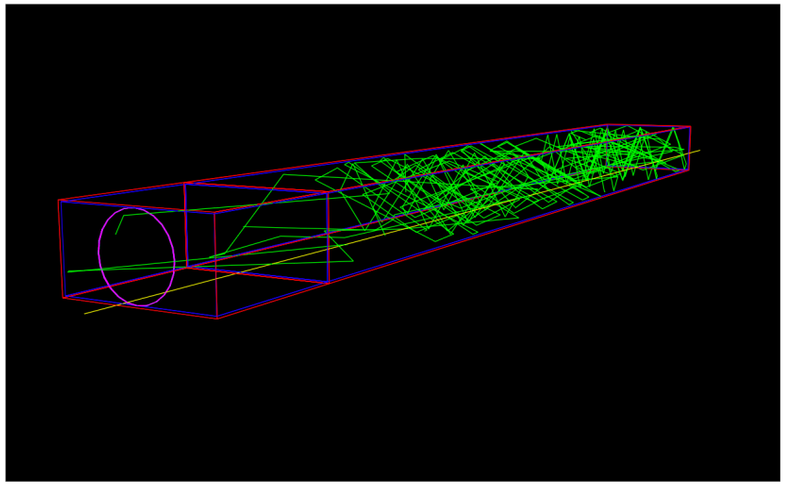
Calibrations

- In-situ charge calibration
  - Calculate N_{PE} produced by a cosmic muon (Q=1e) per PMT and scale (Q^2)
  - Find **N_{PE} = 1 for Q ~ 0.003e** → consistent with result from full GEANT4 simulation
- Timing calibration
  - Cable length, PMT rise time and geometric differences must be calibrated
  - Achieve ~4 ns resolution → easily sufficient for 15 ns window between hits in layers (as assumed in LOI)

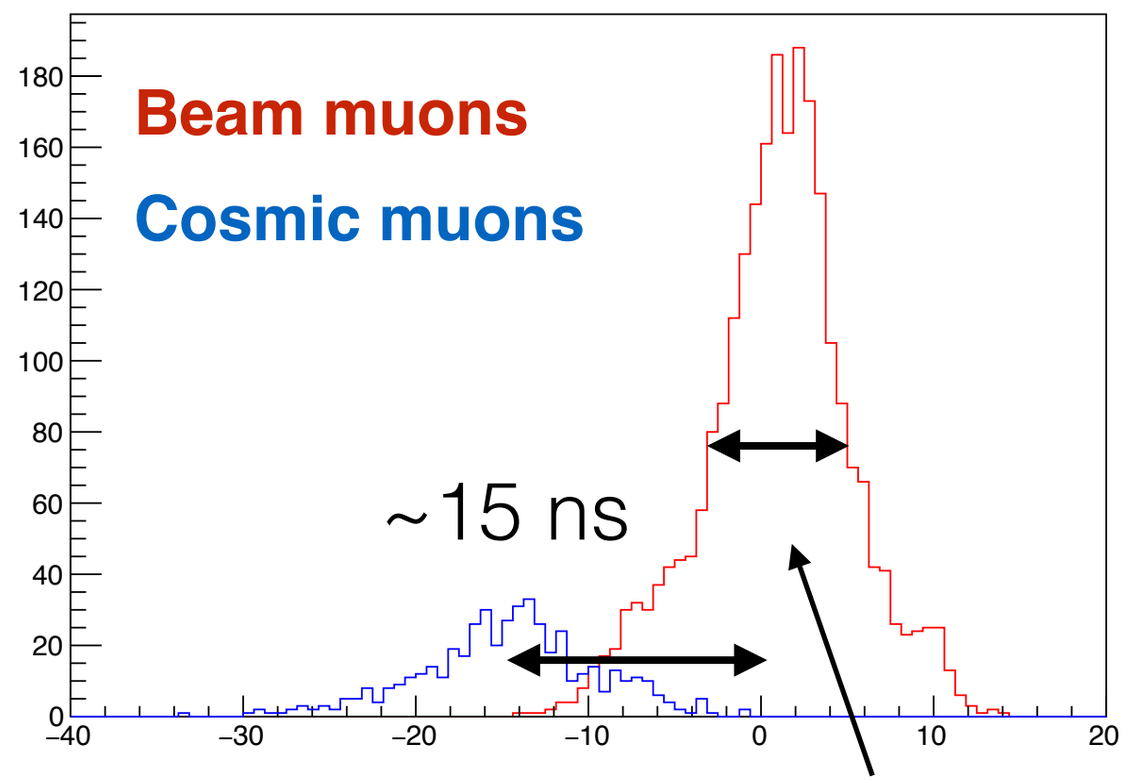
Downgoing cosmics used for charge calibration



GEANT4 simulation



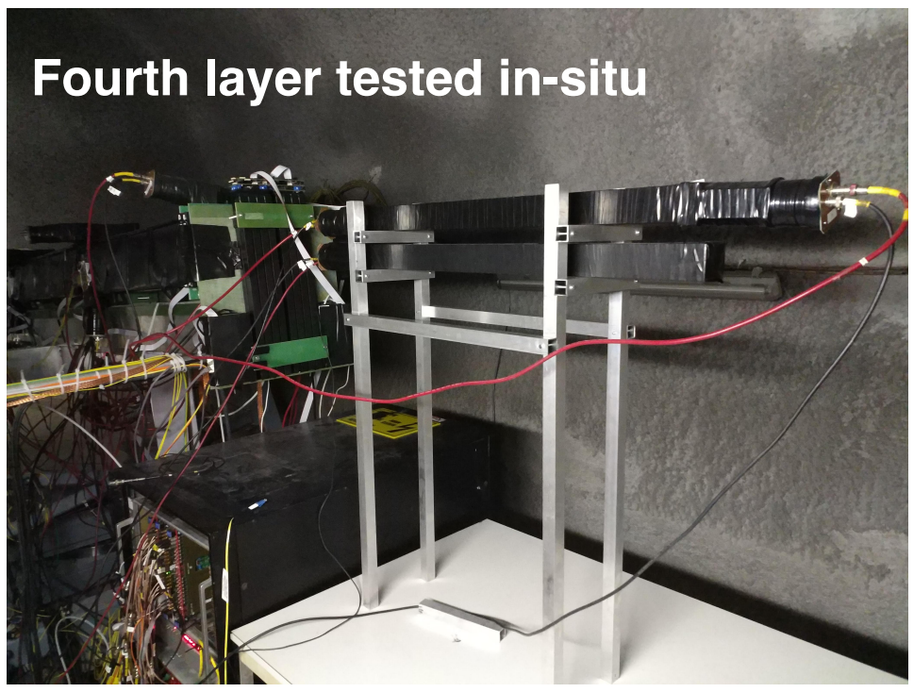
Calibrated time difference between L3 and L1

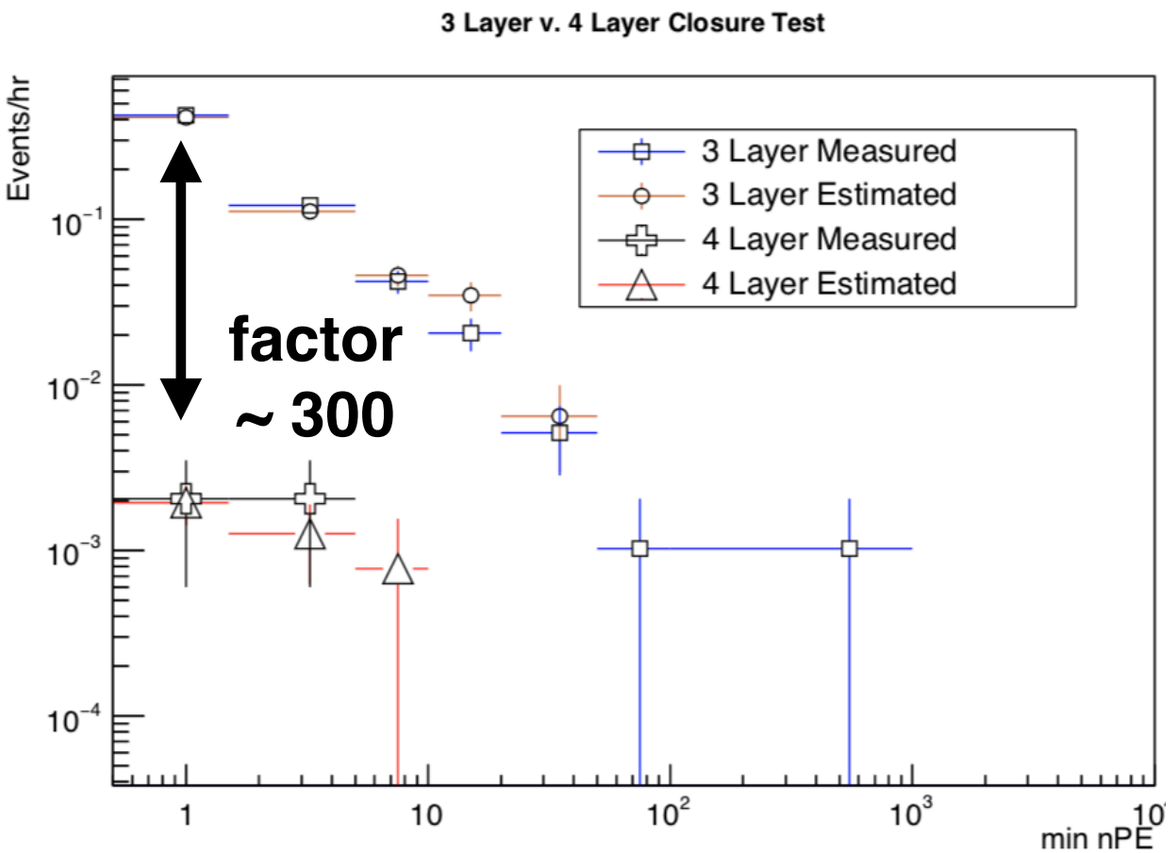


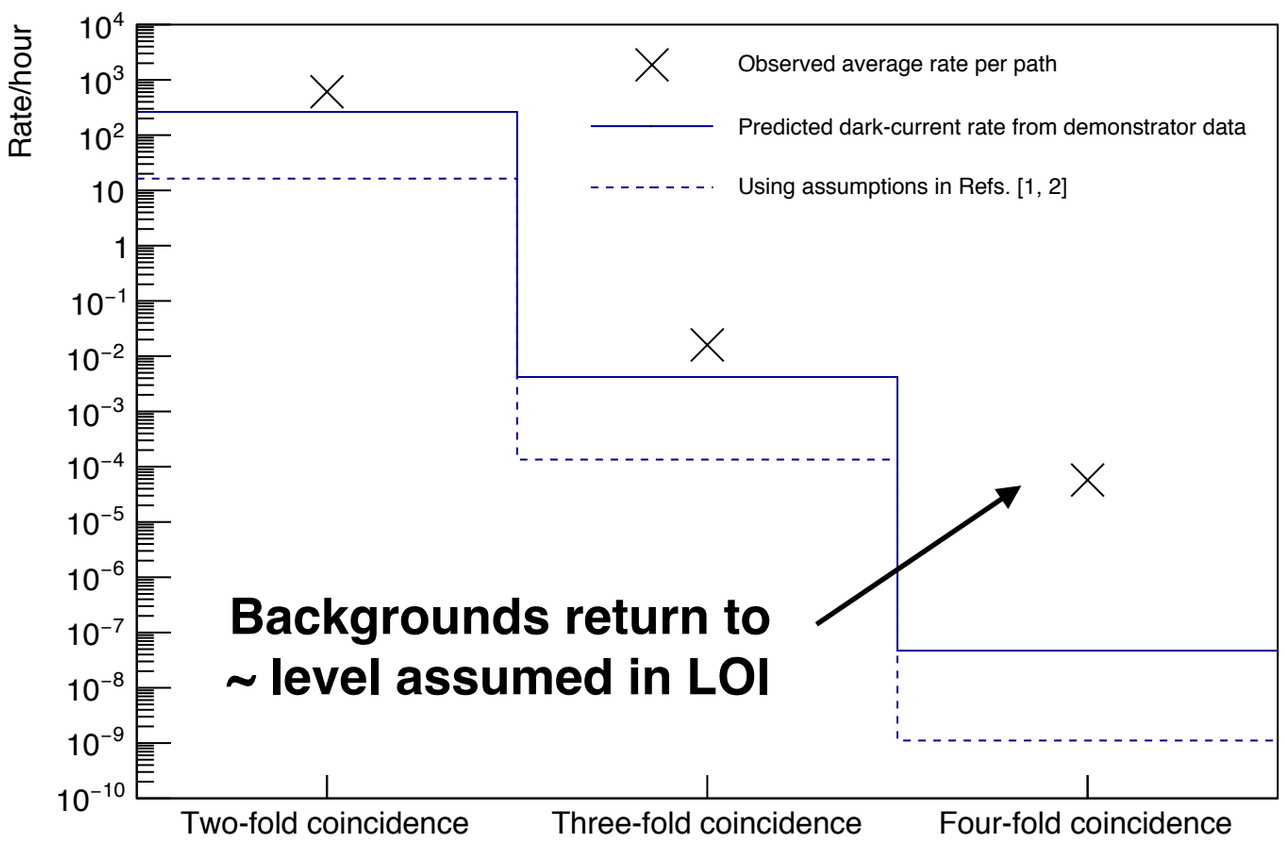
resolution ~ 4 ns

Background measurement

- Detector **aligned** and **calibrated** - measure backgrounds for full milliQan detector
- Major lesson from demonstrator: dark rate subdominant background source
- Motivates update to 'four layer' design → achieve targeted background rate



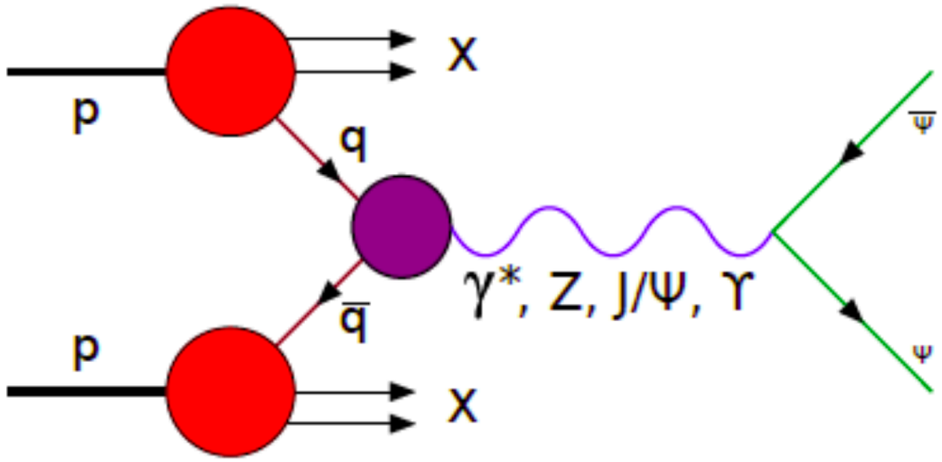




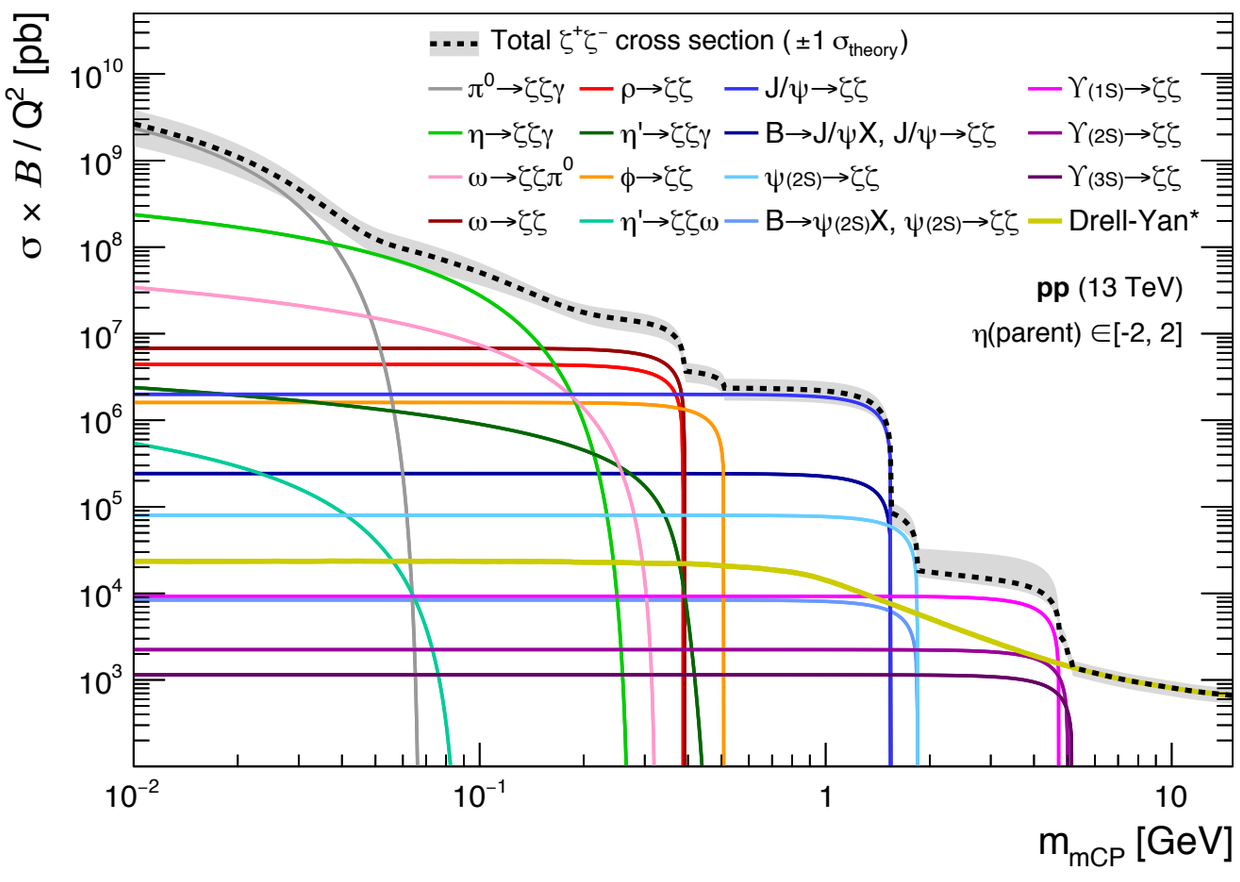
Signal selection: coincident hits within 15 ns (pointing to IP)

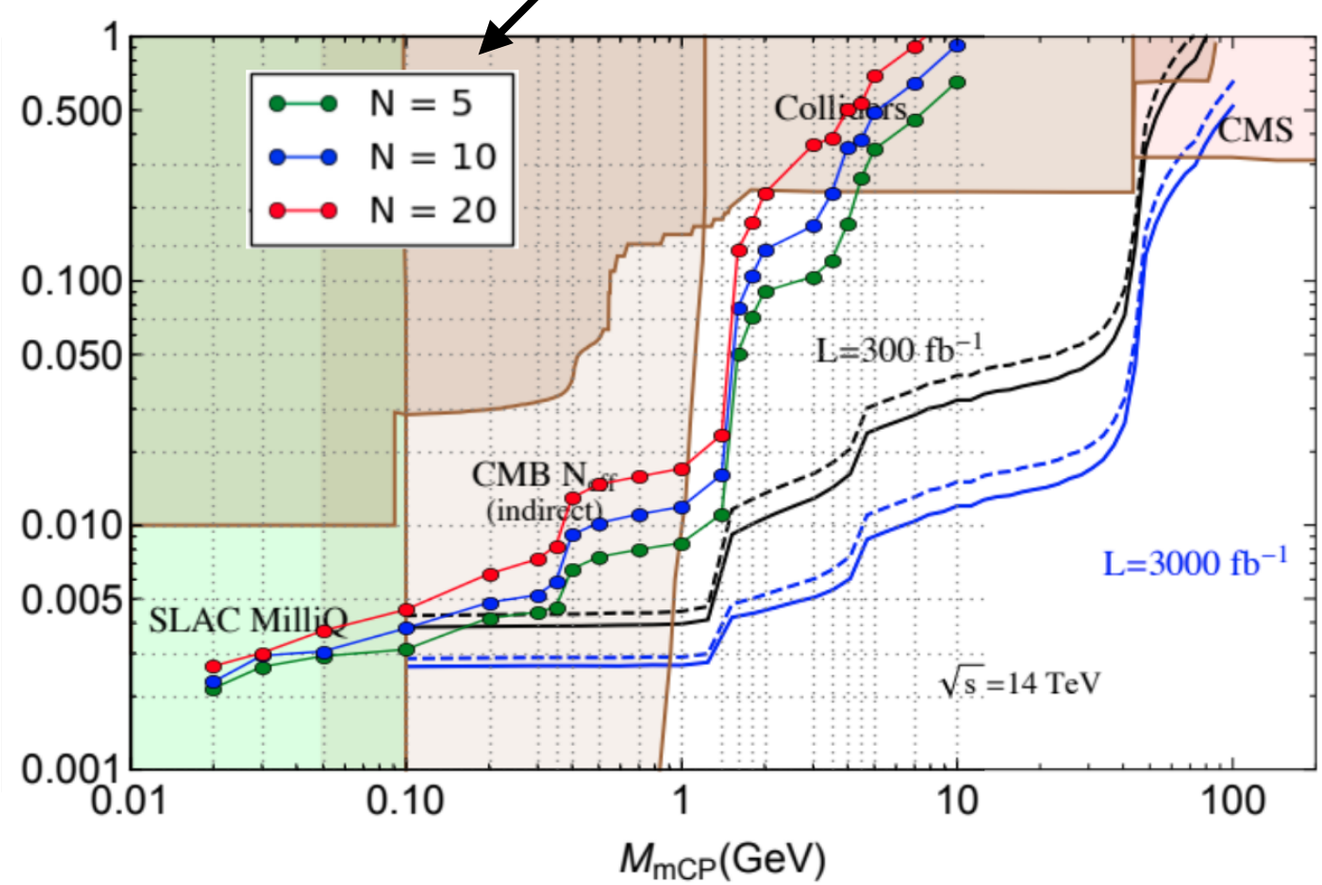
Signal simulation

- Wide range of production mechanisms considered!
- Propagate to detector with response **fully simulated** in GEANT4
- Expect **new sensitivity** already using demonstrator data (search design/backgrounds in backup)



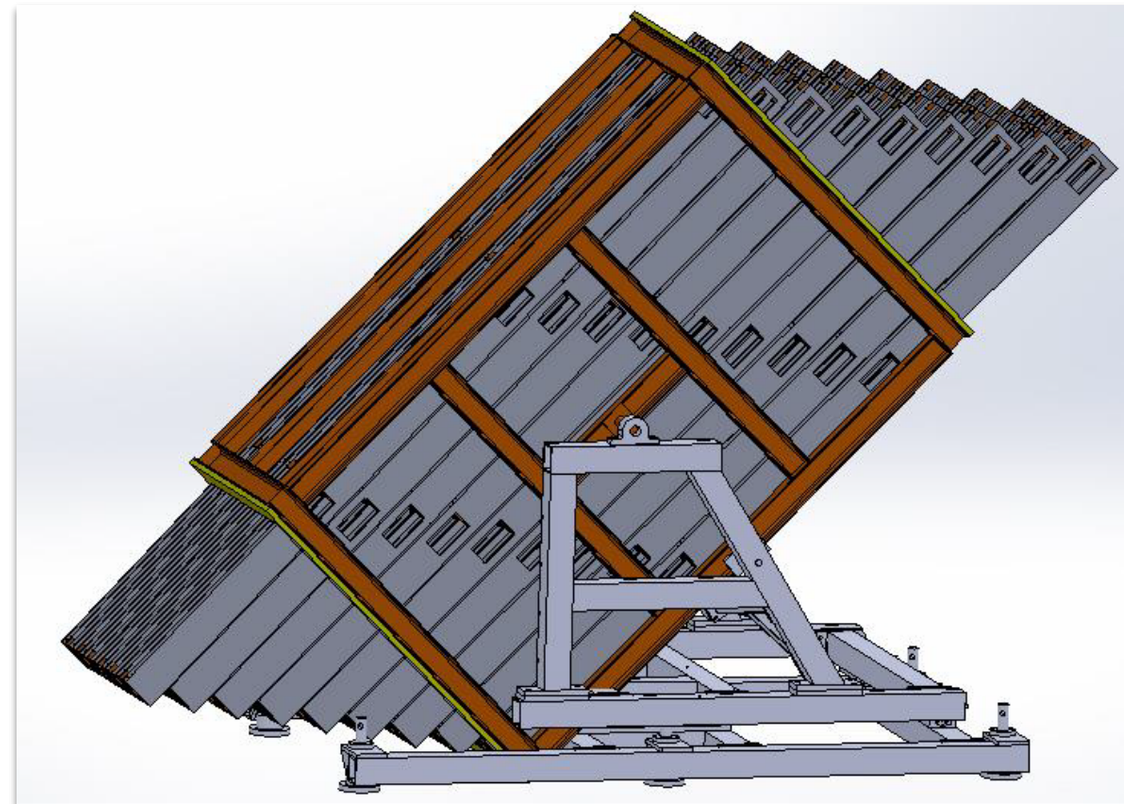
Constant yield contours for triple coincidence ($N_{PE} \geq 1$) from signal **+ demonstrator** simulation



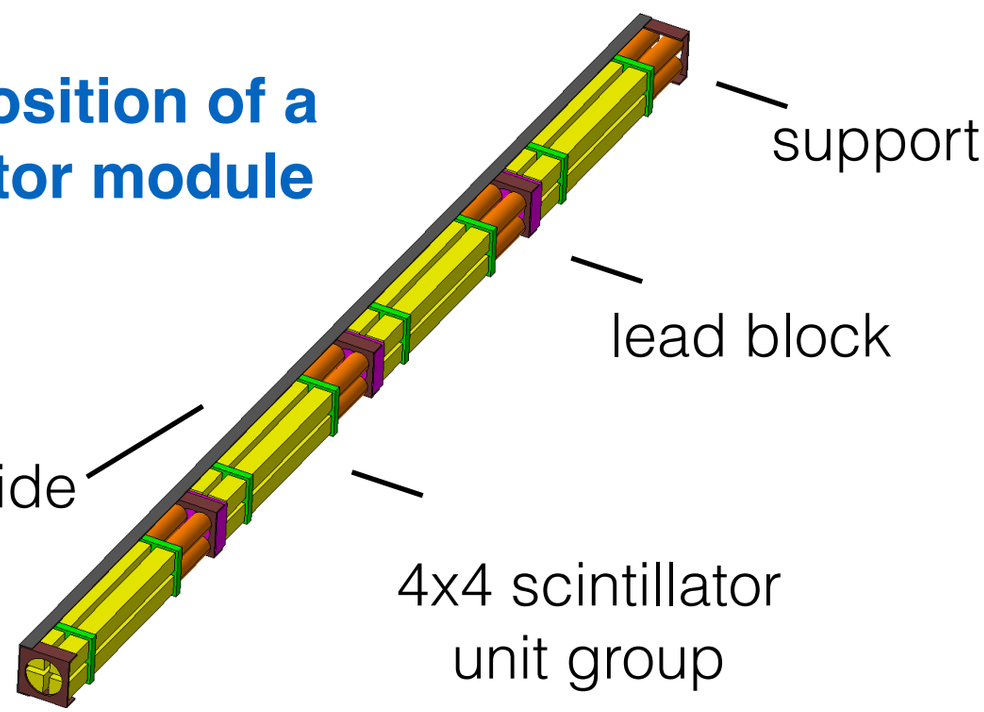


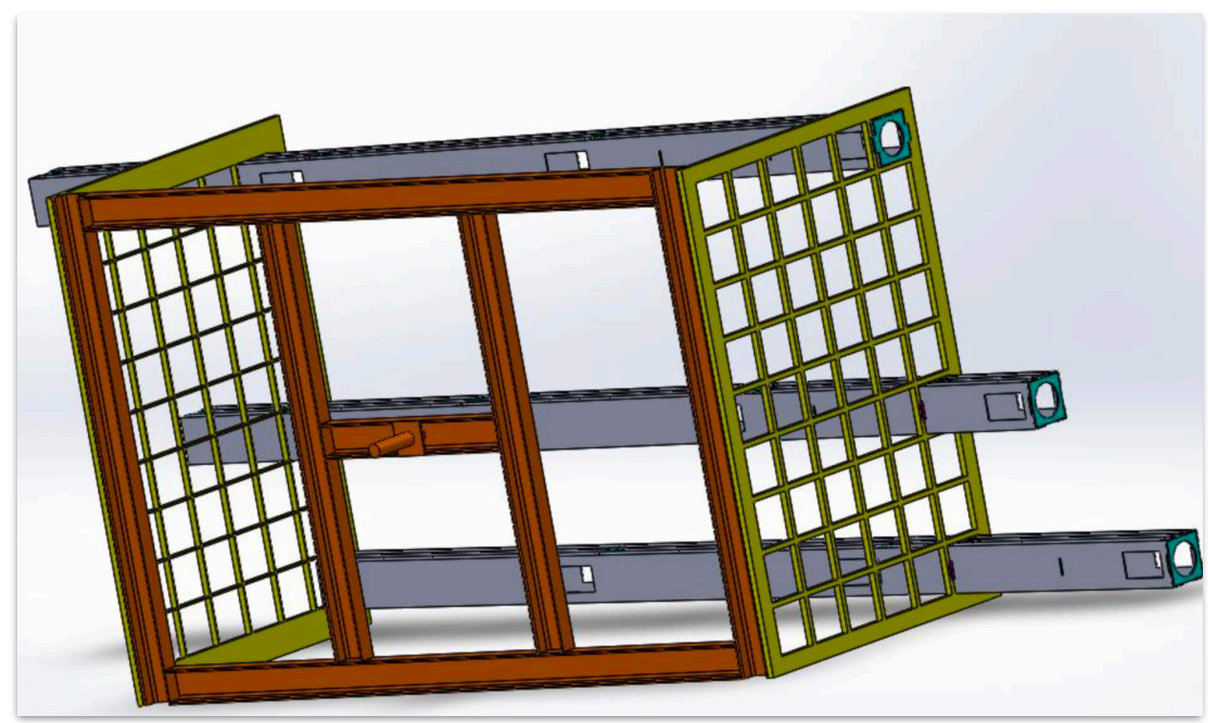
Mechanical structure for full detector

- Plans for mechanical structure finalised with **four layers**
- Constraints: maximum bars in minimal space: two adjacent detectors of 9x6x4x4 = 864 bars (1 x 1 x 3 m)
- Use mounts as in place in drainage gallery



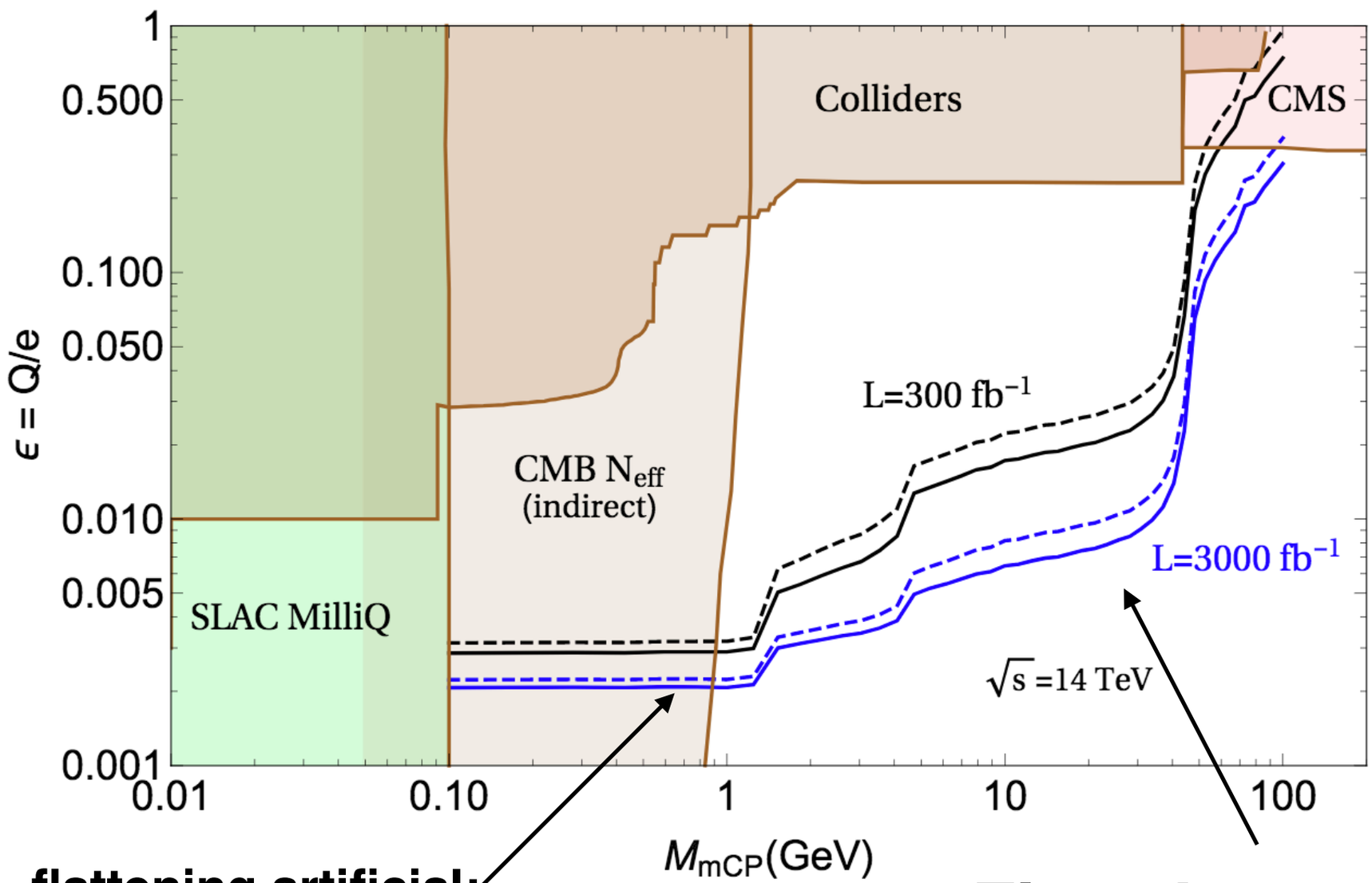
Composition of a detector module





Full detector expected sensitivity

NB - this bound assumes a massless dark photon

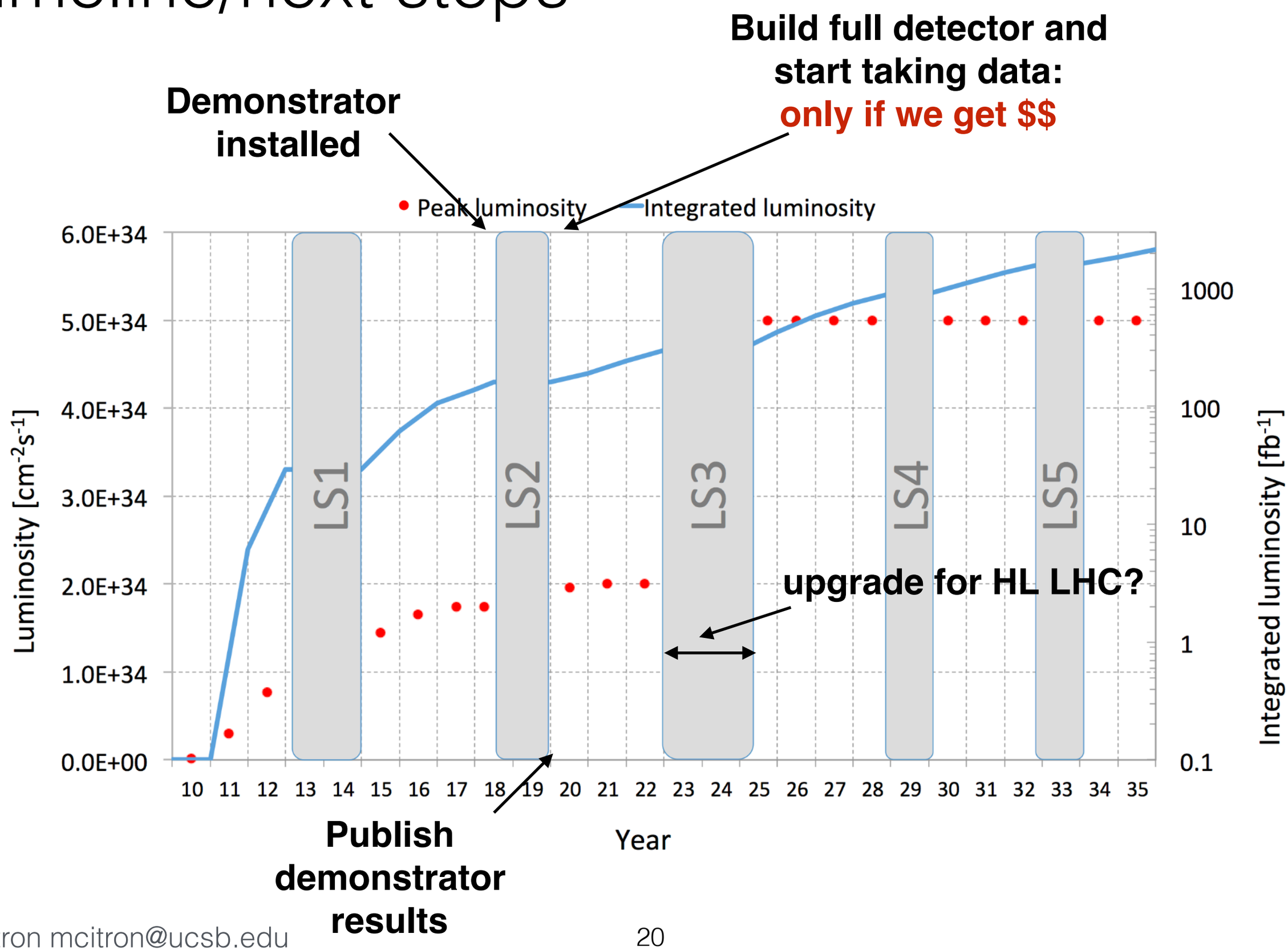


from 2016 LOI - update coming (very) soon!

flattening artificial: no mCP production from QCD/ hadronic processes included (only DY/prompt resonances)!

First detector sensitive to ~mCP at GeV ranges!

Timeline/next steps



Conclusions

- The milliQan detector can provide **unique sensitivity** to milli-charged particles
- Built, commissioned and operated small prototype to **prove feasibility** and **measure background** rate for full detector
  - Plan publication using data collected in 2018 with new sensitivity!
- Signal generation, propagation and detector response **fully simulated**
- **Full mechanical** design for detector finalised
- We are ready for construction but …
  - No funding secured so far despite (well reviewed) proposals to various agencies/foundations
  - Without funding soon, the opportunity to carry out this interesting (and relatively cheap) extension of the LHC physics program will be in jeopardy

milliQan collaboration

C. Hill,
B. Francis,
M. Carrigan

D. Stuart, C. Campagnari,
M. Citron, R. Heller,
B. Marsh

A. Haas,
G. Beauregard

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

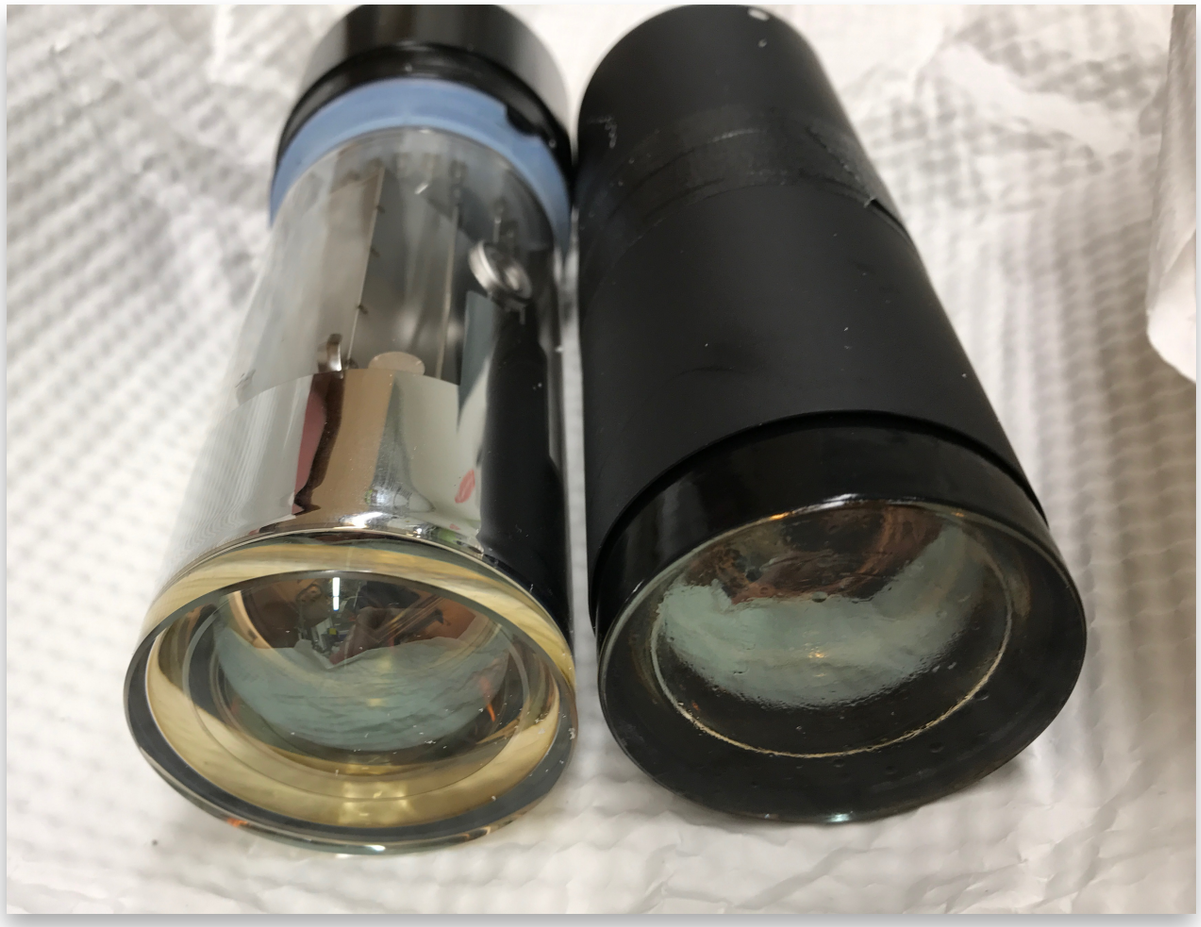
This speaker supported by
funding from DOE Office of Science

Backup

PMTs

High gain and fast
(but expensive)

Older/slower but free
(taken from older experiment)



Hamamatsu R7725

Electron Tube 9814B

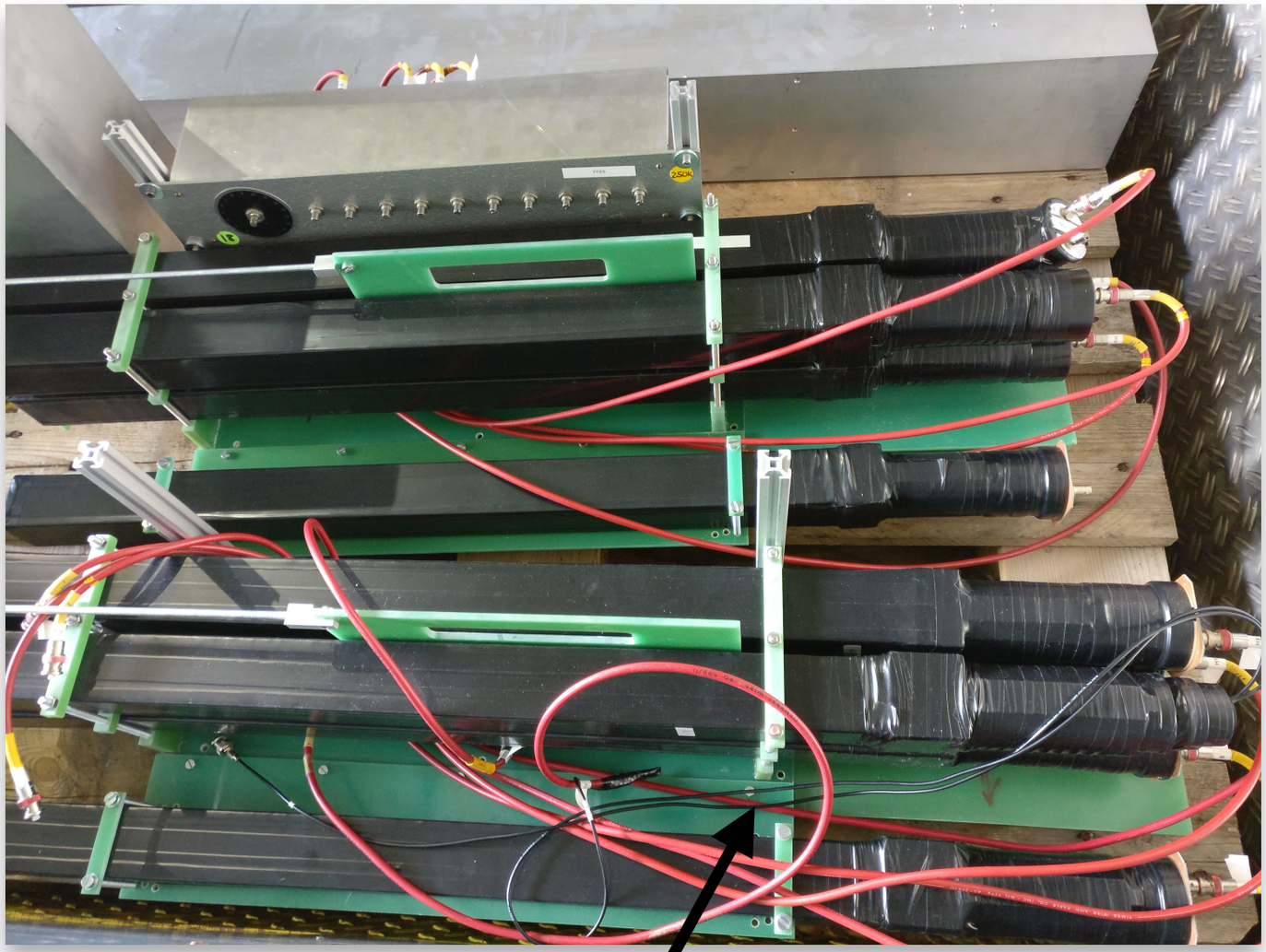
Hamamatsu R878

Demonstrator used to find strengths/
weaknesses of various PMT species

Module assembly

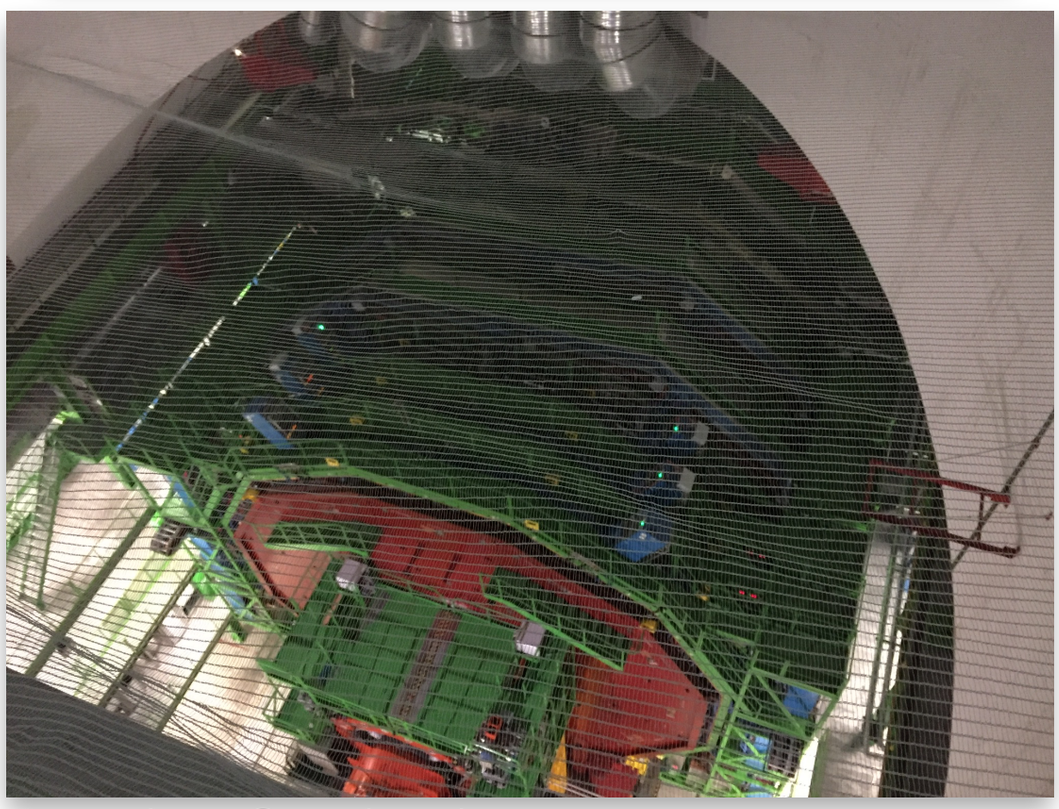
3D printed
PMT casing

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

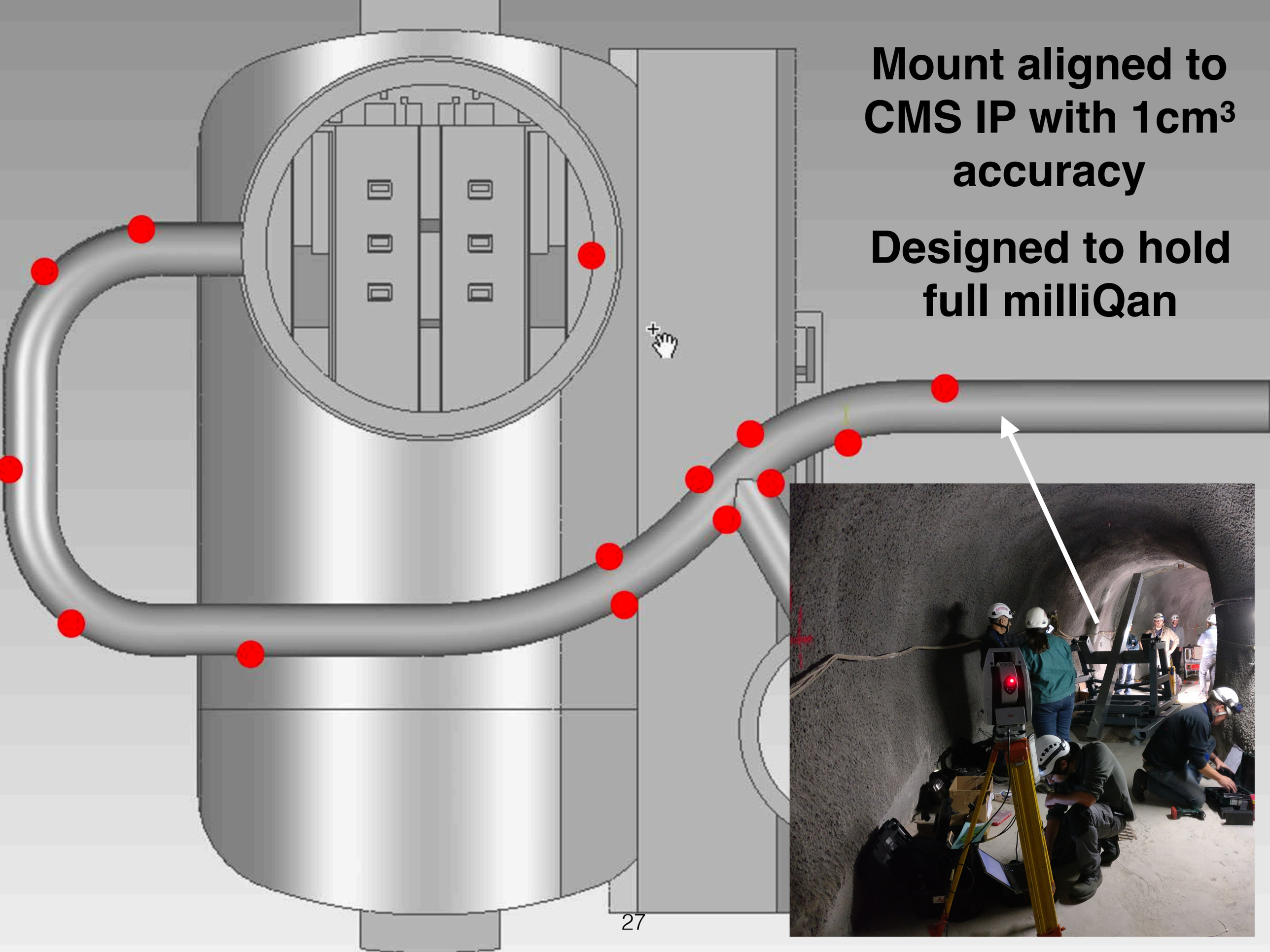


Fibre glass mounts
for each layer

Going underground (via the CMS shaft)



Modules assembled on the surface and then lowered to gallery


Mount aligned to CMS IP with 1cm³ accuracy
Designed to hold full milliQan

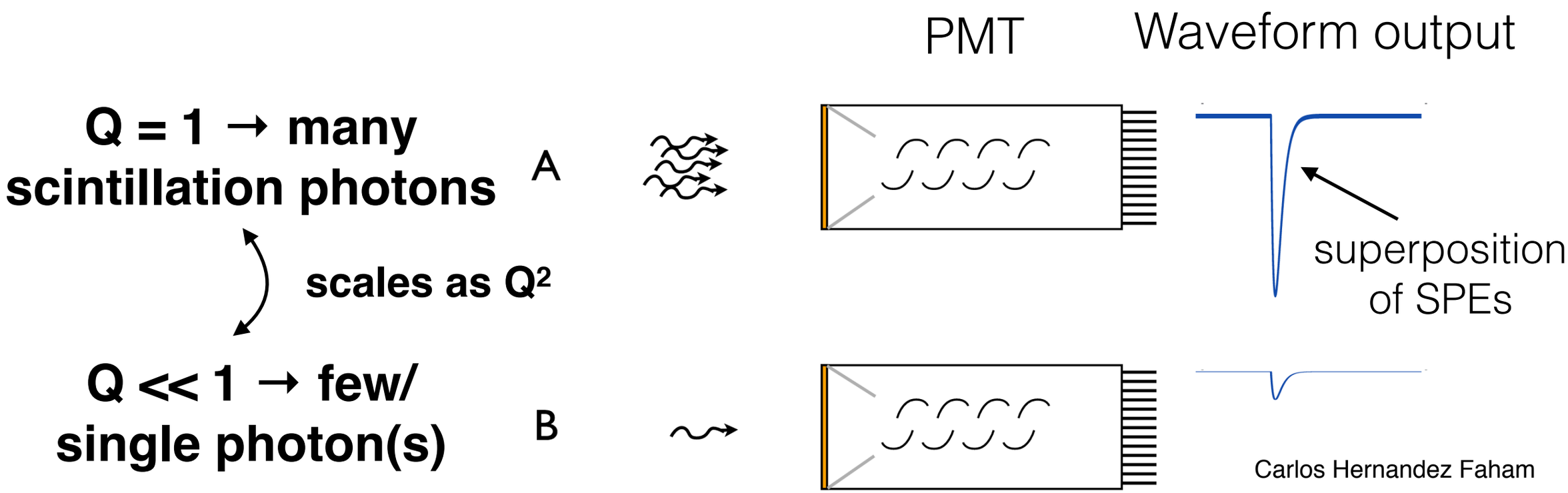
Backgrounds

- Beam backgrounds rejected by rock
  - Leaves ~15 muons/minute which reach detector
- Cosmic muons
  - Through-going rate few/minute (~1% rate at surface)
- Showers of n/γ/e from beam/cosmic muons in rock/detector material
- Random overlap of dark pulses within PMTs
- Radiation within PMTs and cavern walls

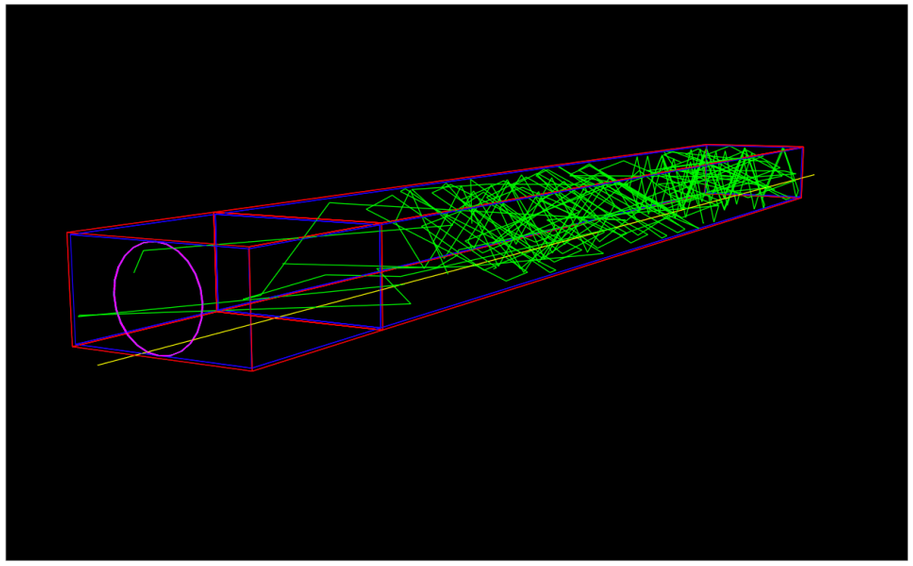
Muons clearly distinguishable from signal

Reject with multi-layer coincidence and active veto requirements

In-situ charge calibration

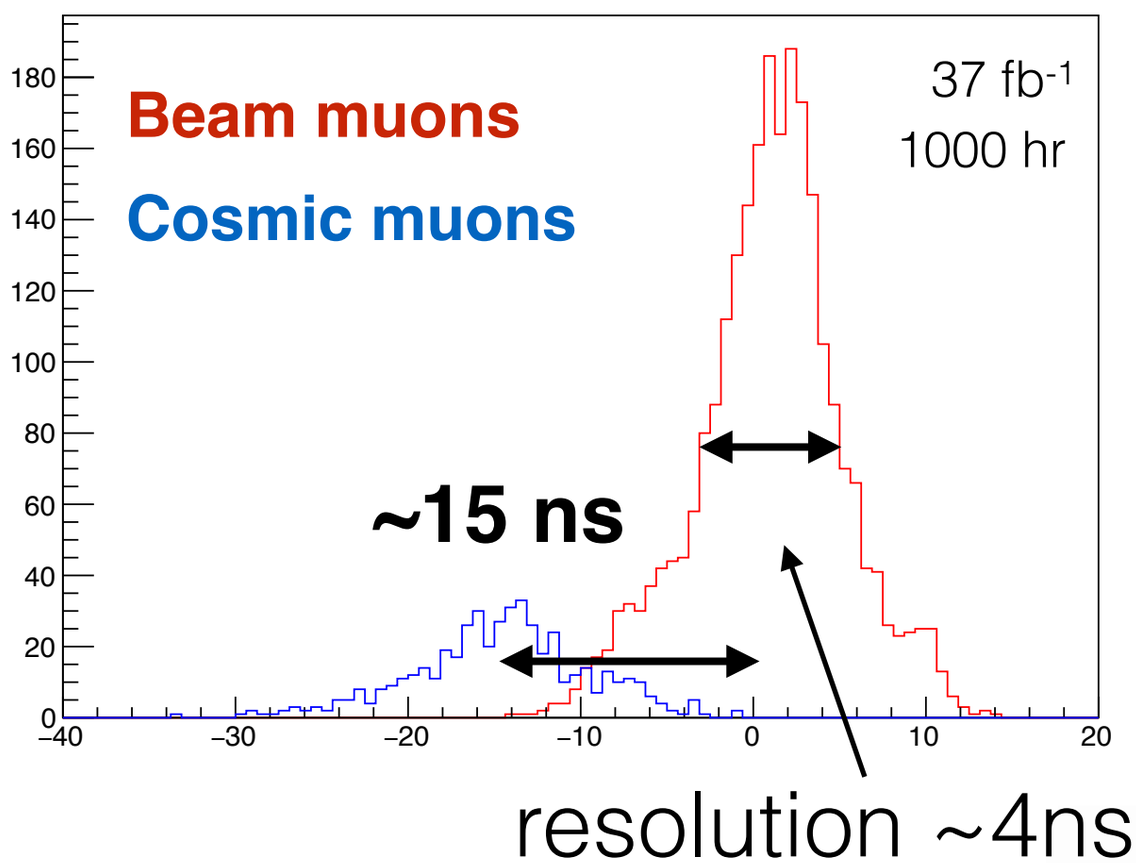


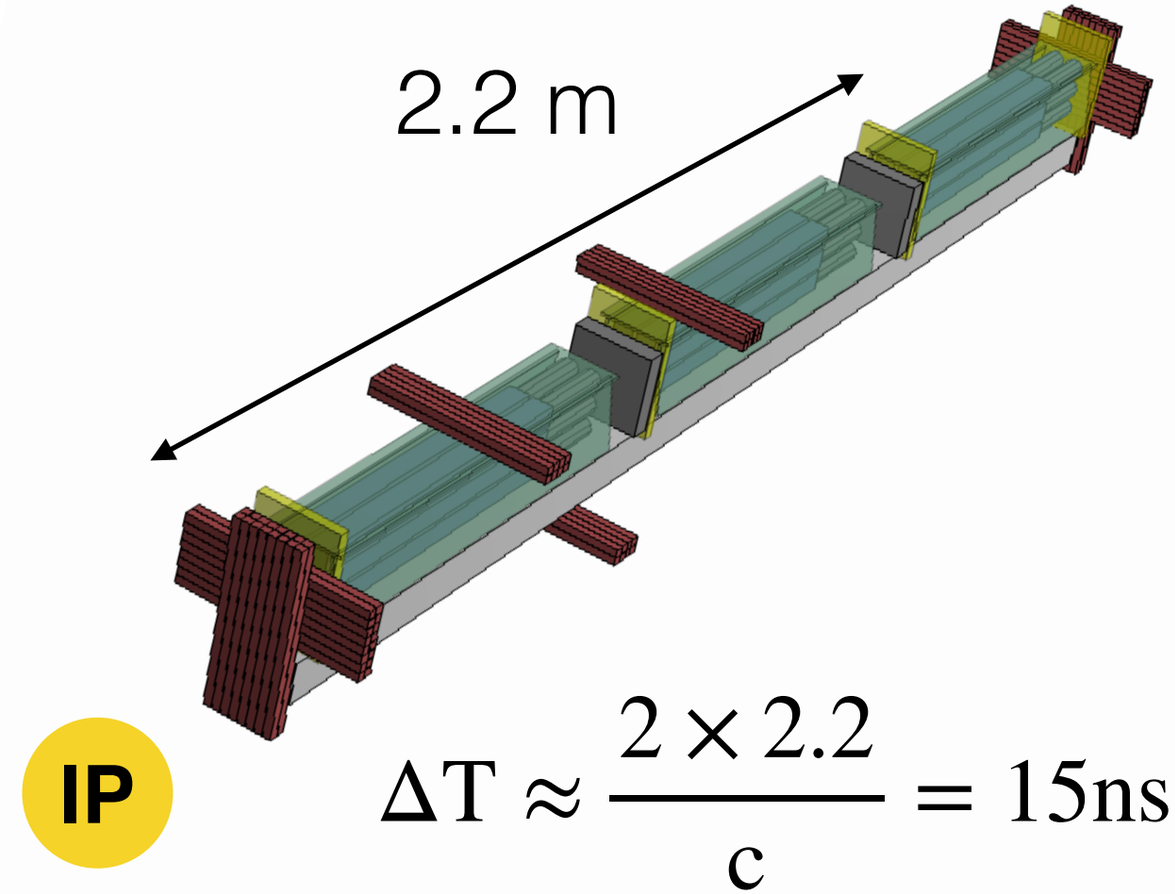
- Need to know number of photons (N_{PE}) produced for a given Q
- Calculate N_{PE} produced by a cosmic muon (Q=1e) and scale (Q^2)
- N_{PE}(Q=1e) = pulse area (cosmic)/pulse area single photon (SPE)
- Find **N_{PE} = 1 for Q ~ 0.003e** → consistent with result from full GEANT4 simulation



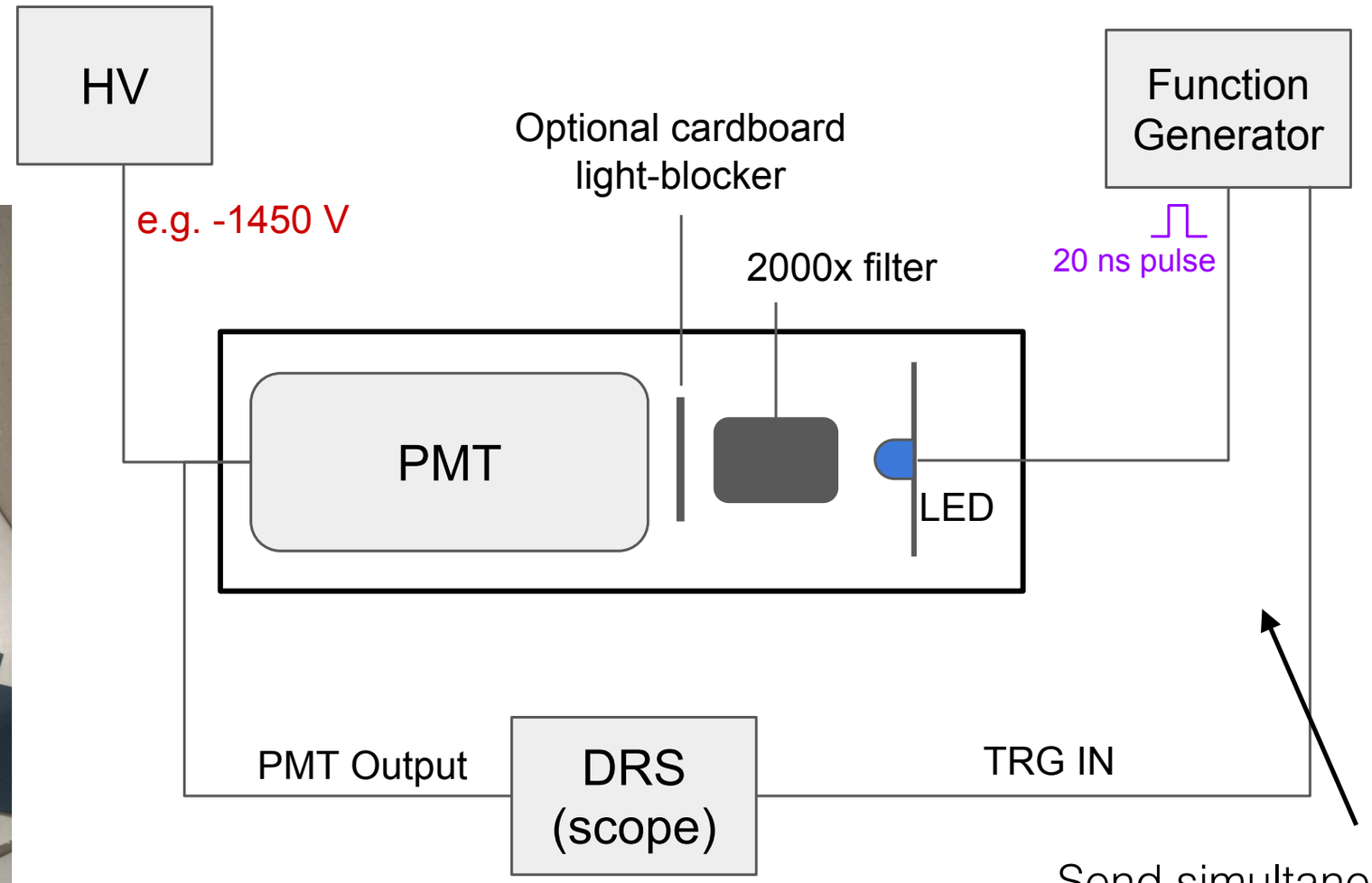
Thru-going particle timing

- Reject random dark rate background using small time window between hits in layer
  - Cable length, PMT rise time and geometric differences must be calibrated
- Resolution ~4ns - easily sufficient for triple coincidence in time window at least as small as assumed in LOI (15ns)!



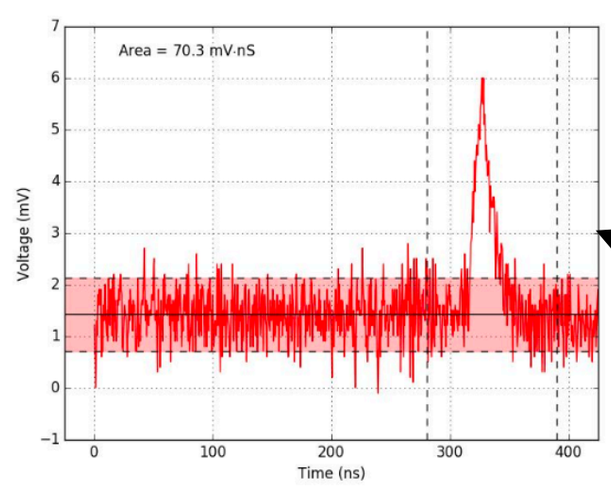


SPE calibration using LED



Send simultaneous LED pulse and trigger

Digitise and record waveforms



Measure pulse area using integral of window

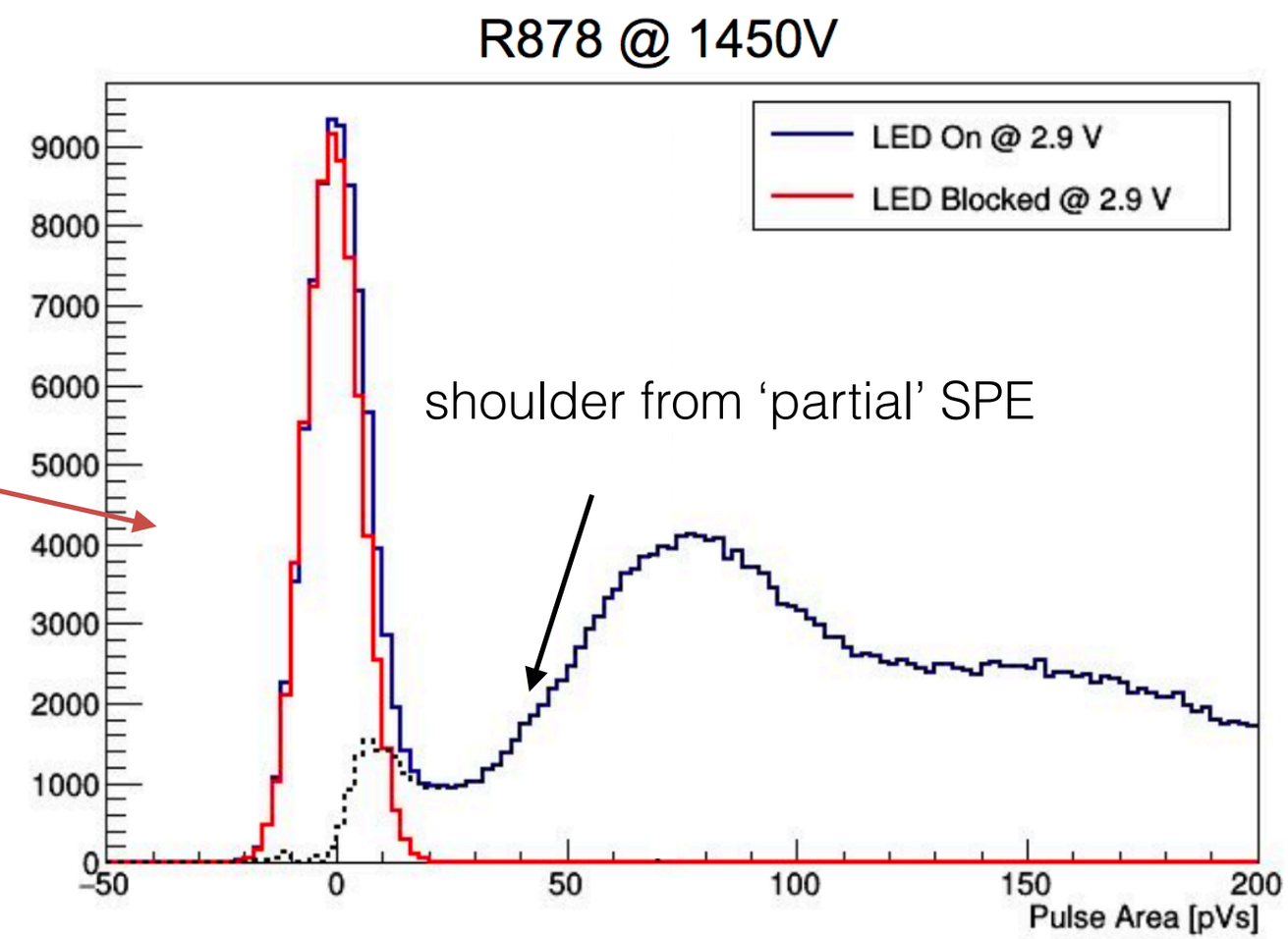
Will show results for example PMT (R878)

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

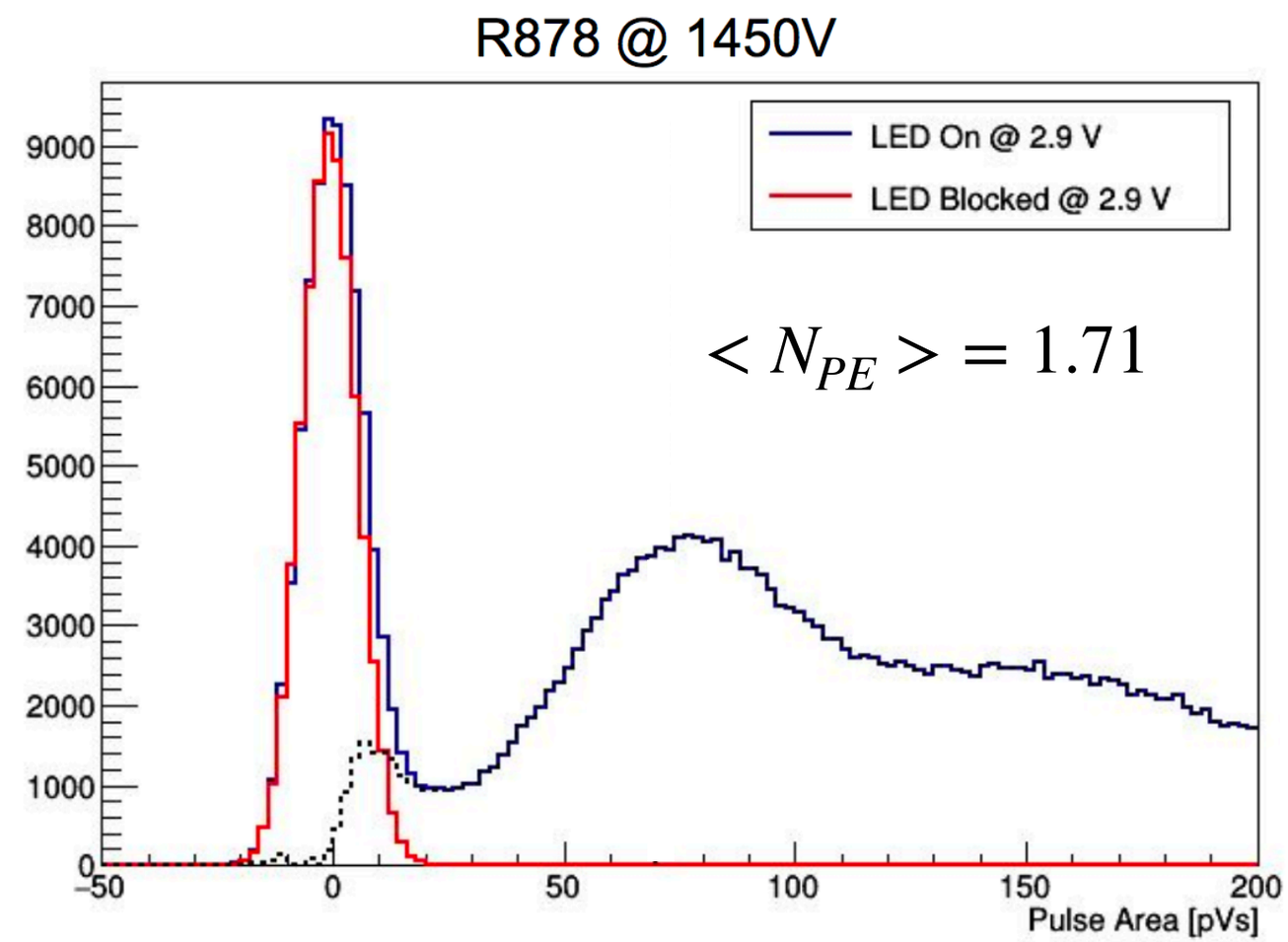
Now calculate SPE area

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):

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

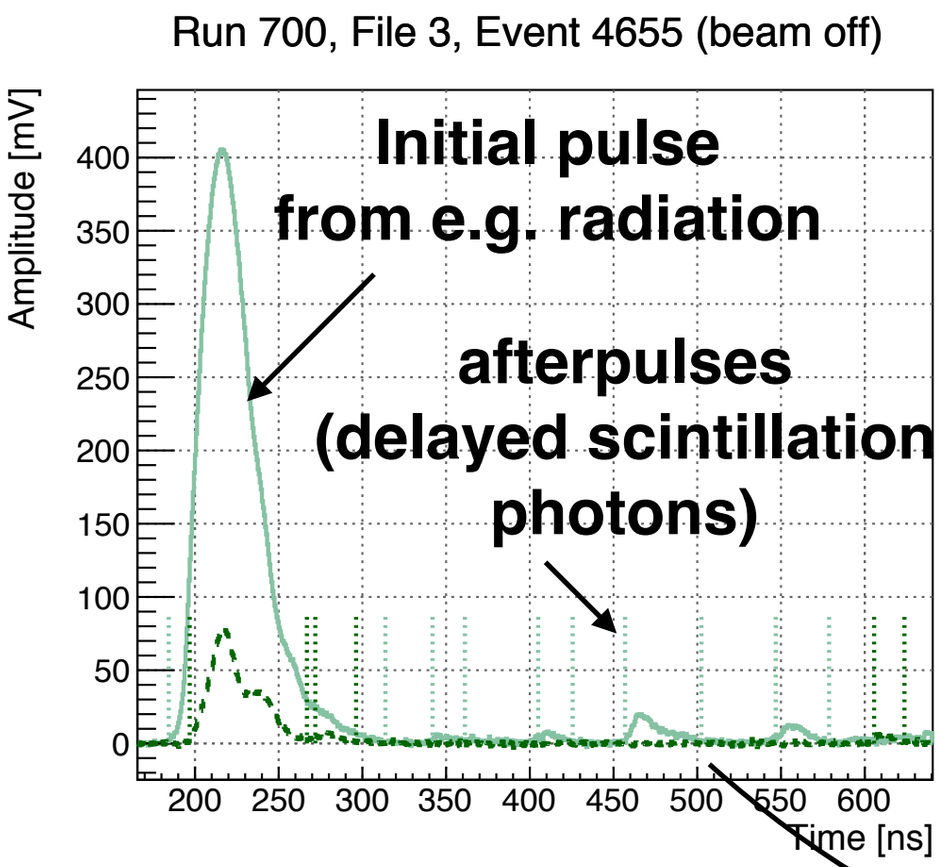
$$\sigma = 32 \text{ pVs}$$

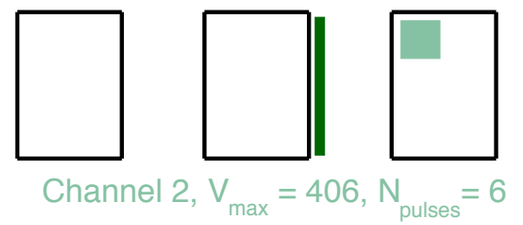
method from Saldanha et al., https://arxiv.org/abs/1602.03150

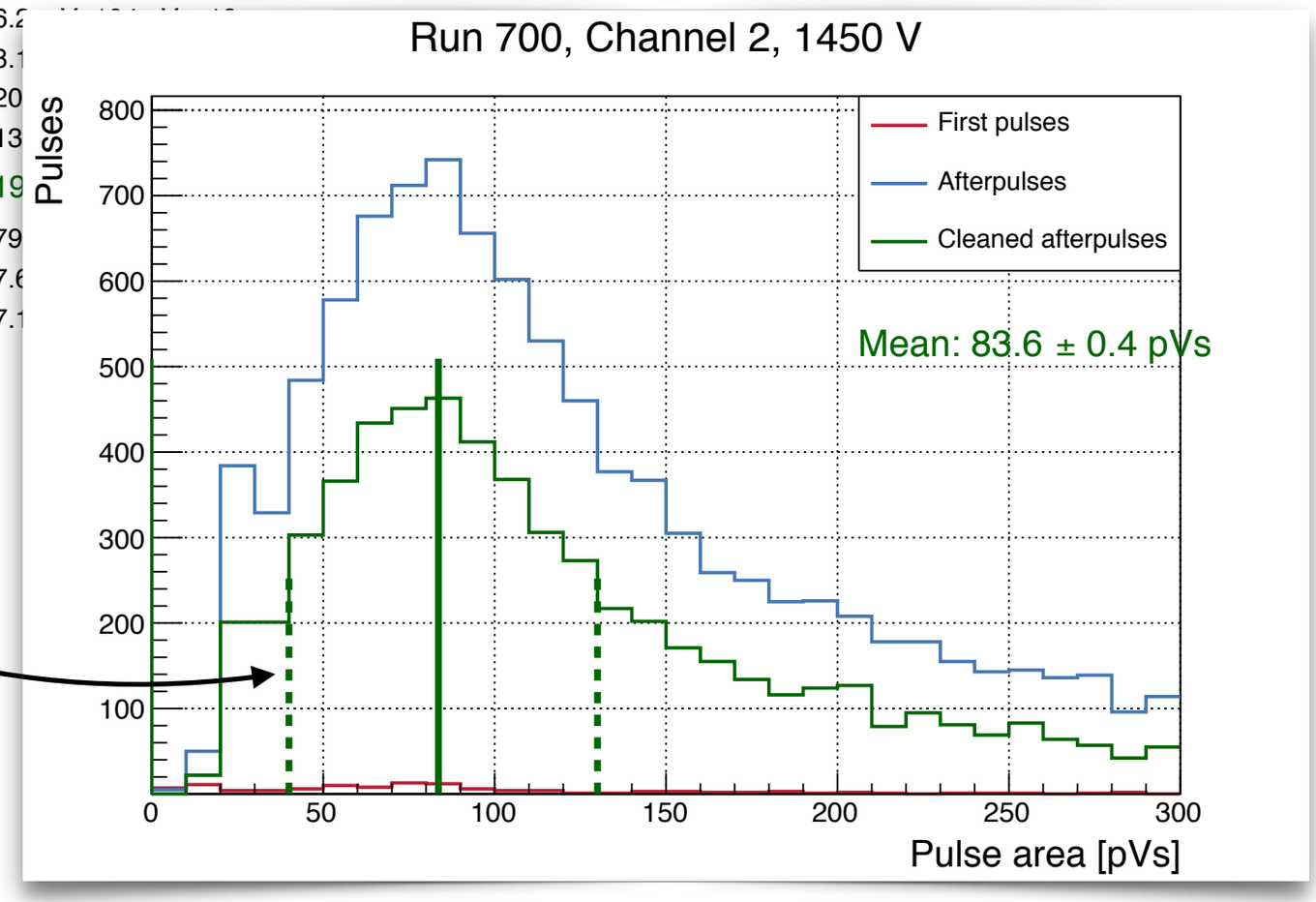
SPE calibration in-situ

- Calibration using LED ‘gold standard’ but can’t use this method in-situ
  - Have carried out for both an R7725 and R878 PMT
- Need method to approximate SPE area during data taking
  - In case of drift, effect of magnetic field (see later), etc…
- Calibrate using delayed scintillation pulses
  - Caveats: contamination from ion afterpulses, potential bias from pulse identification, no accounting for ‘partial’ SPEs

Calibration from delayed scintillation pulses





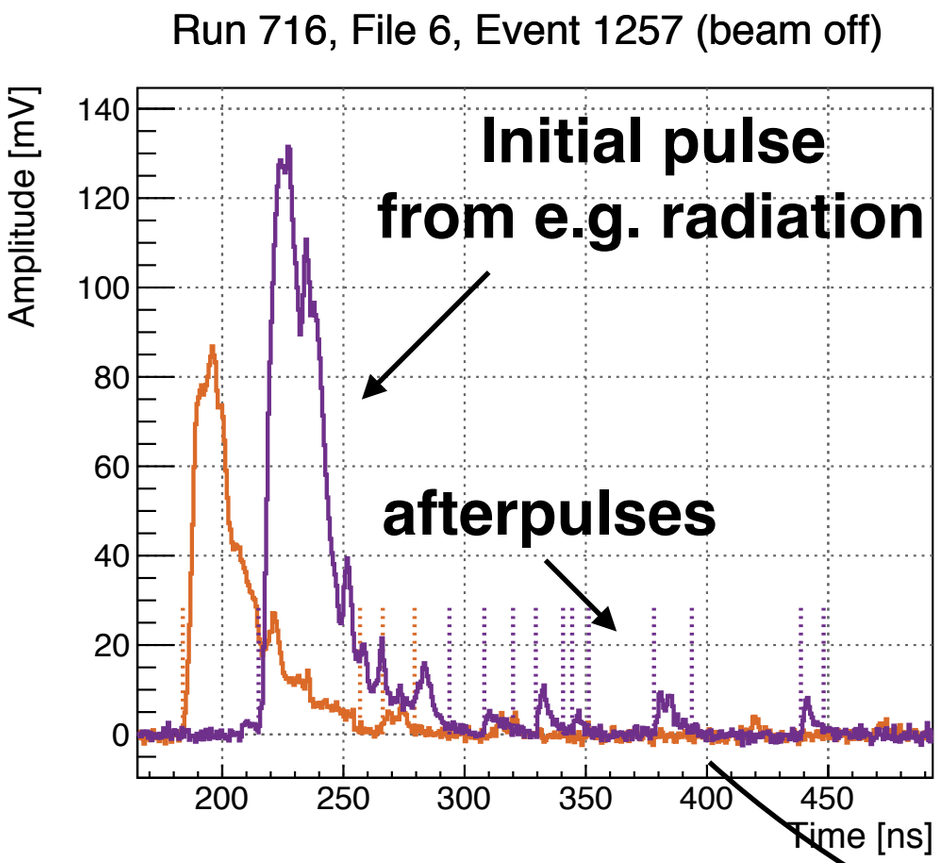


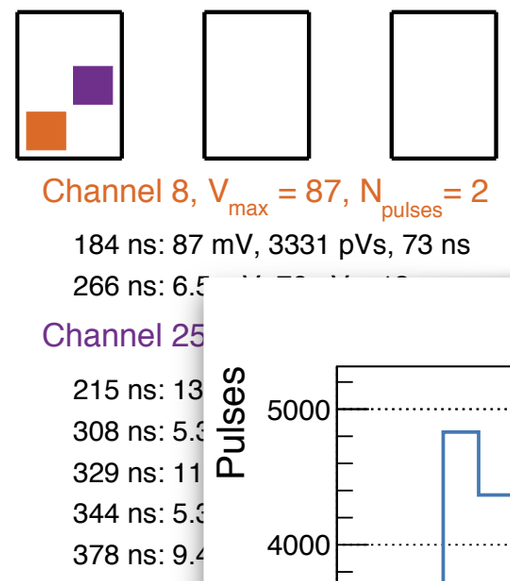
Build up pulse area distribution from 'cleaned afterpulses' (no pulse in preceding 20ns)

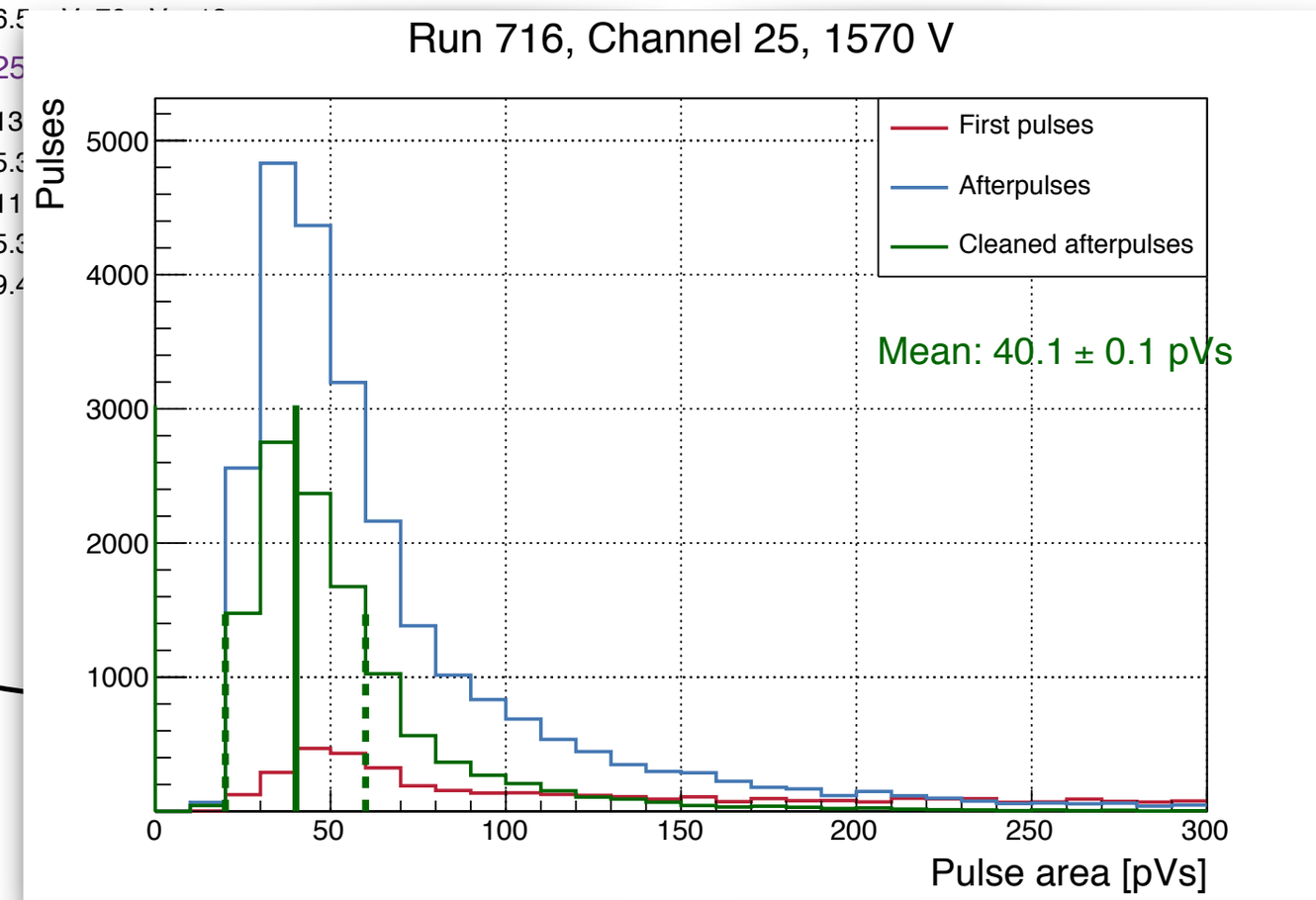
e.g. R878 PMT

Mean within half-width-max gives SPE pulse area

Calibration from delayed scintillation pulses





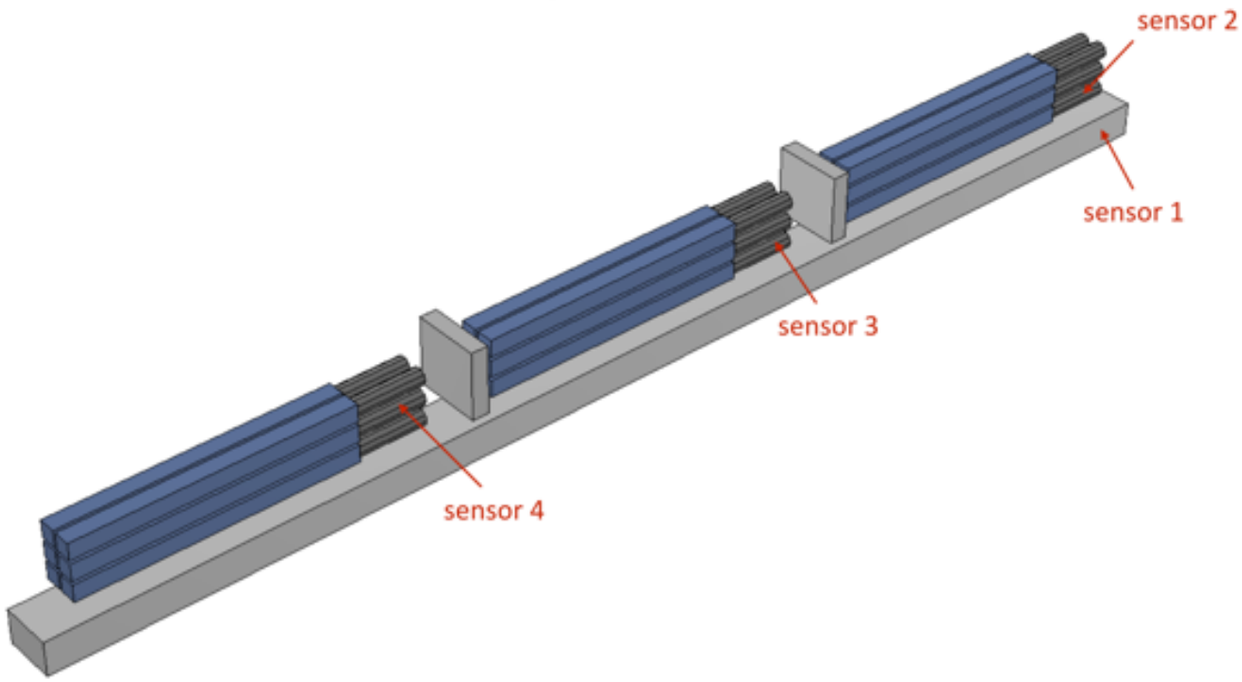


Build up pulse area distribution from 'cleaned afterpulses' (no pulse in preceding 20ns)

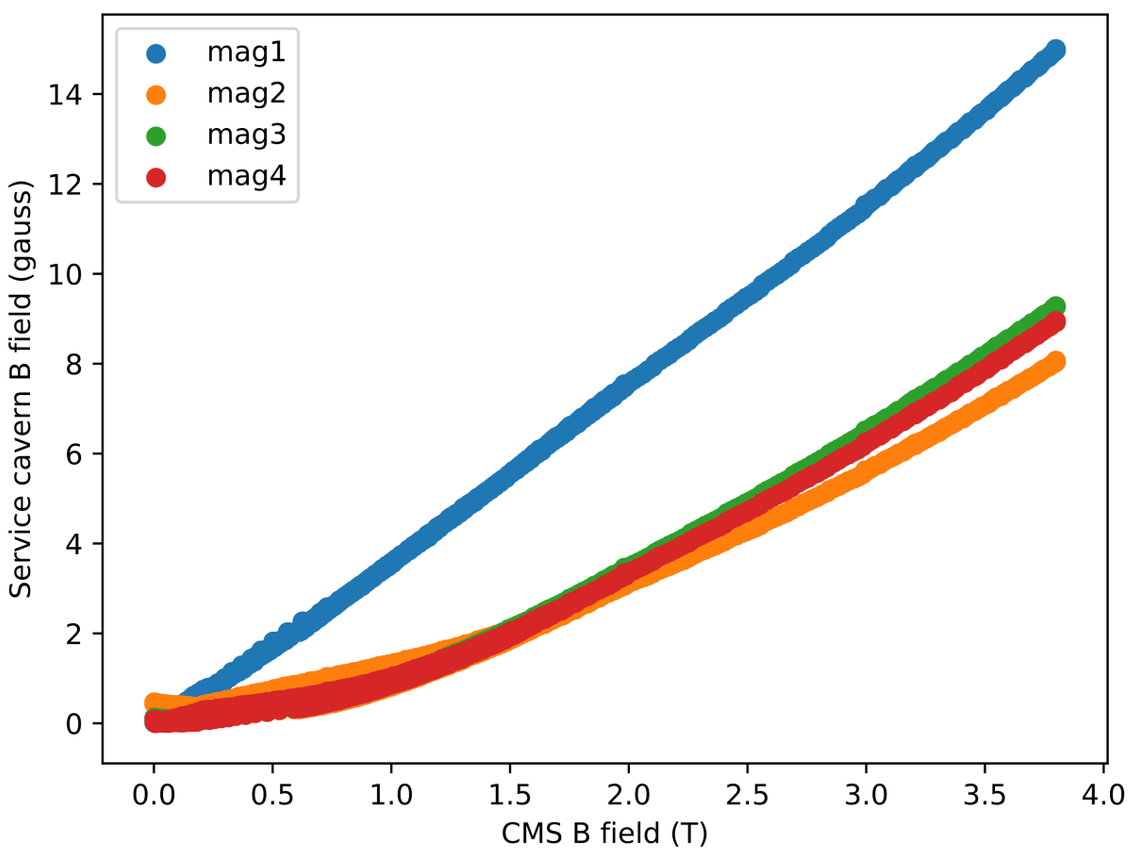
e.g. ET9814B PMT

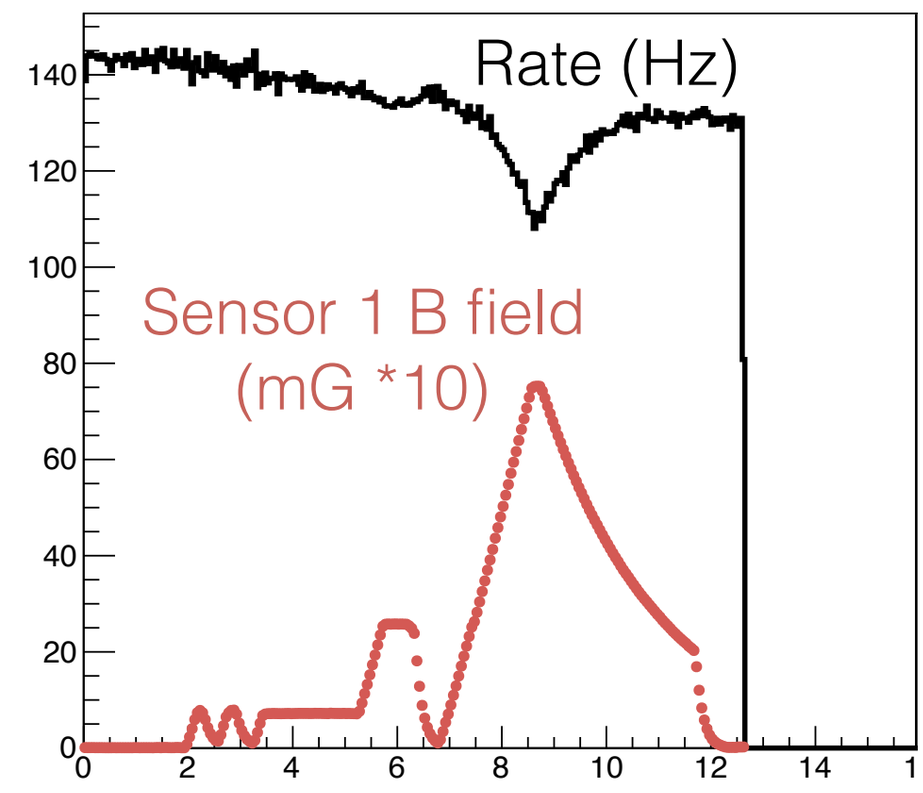
Mean within half-width-max gives SPE pulse area

Effect of magnetic field



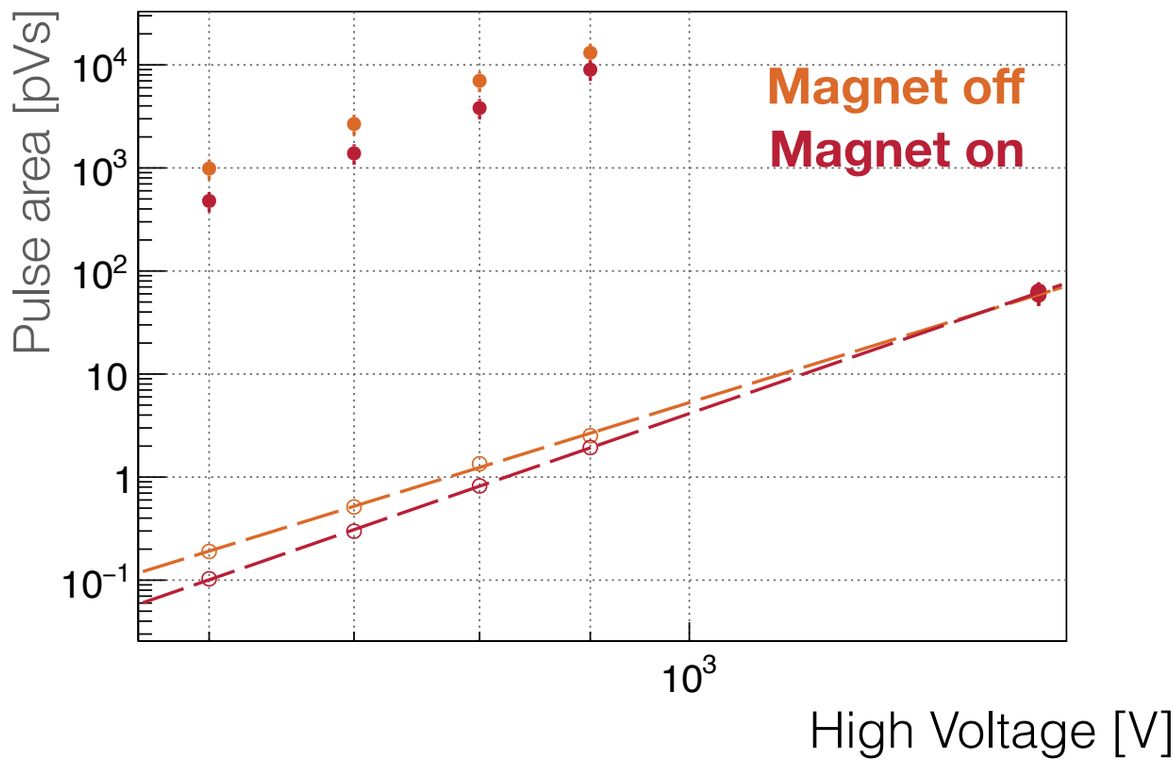
- Drainage gallery has residual magnetic field from CMS
- Measure field both inside and outside of PMT shielding (mu-metal)
- Look at effect on PMTs



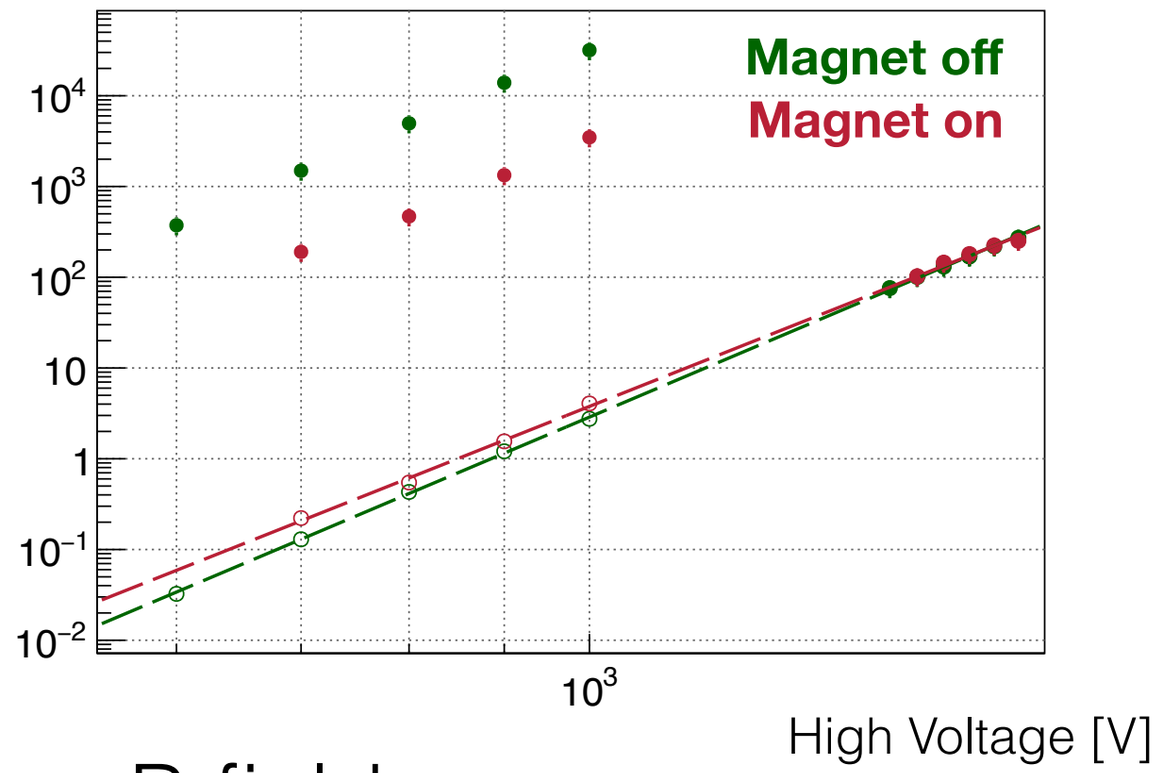


Effect of magnetic field

e.g. R878

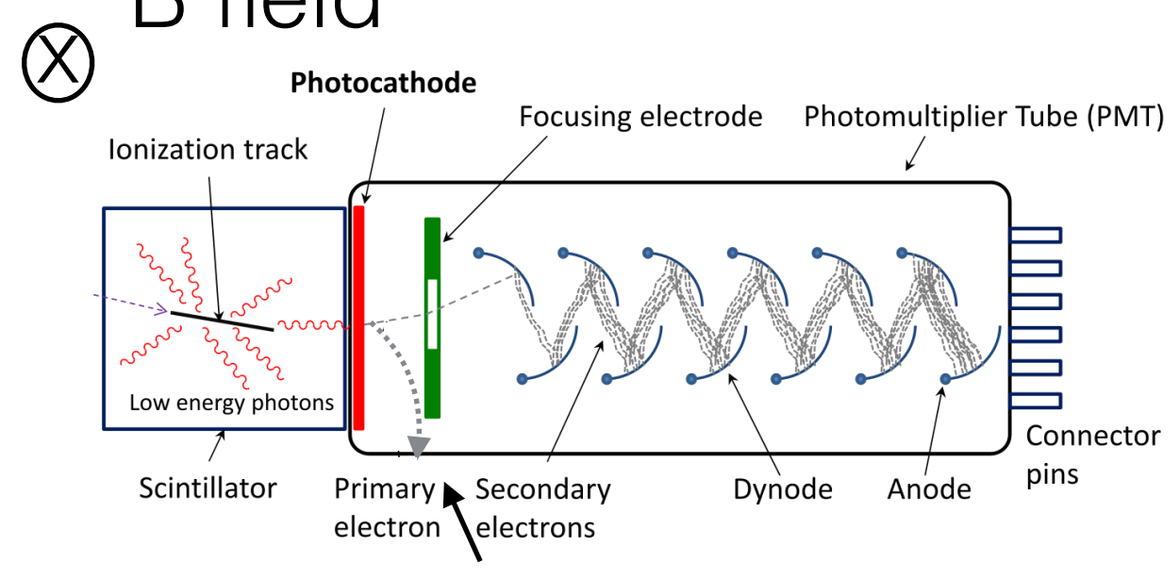


e.g. R7725



- B field can have large effect on NPE as primary electrons can be deflected
- Shows importance of in-situ calibration
- Size of effect varies between species and orientation of PMTs in field
  - Important consideration for full detector (ETs/878s work well!)

B field

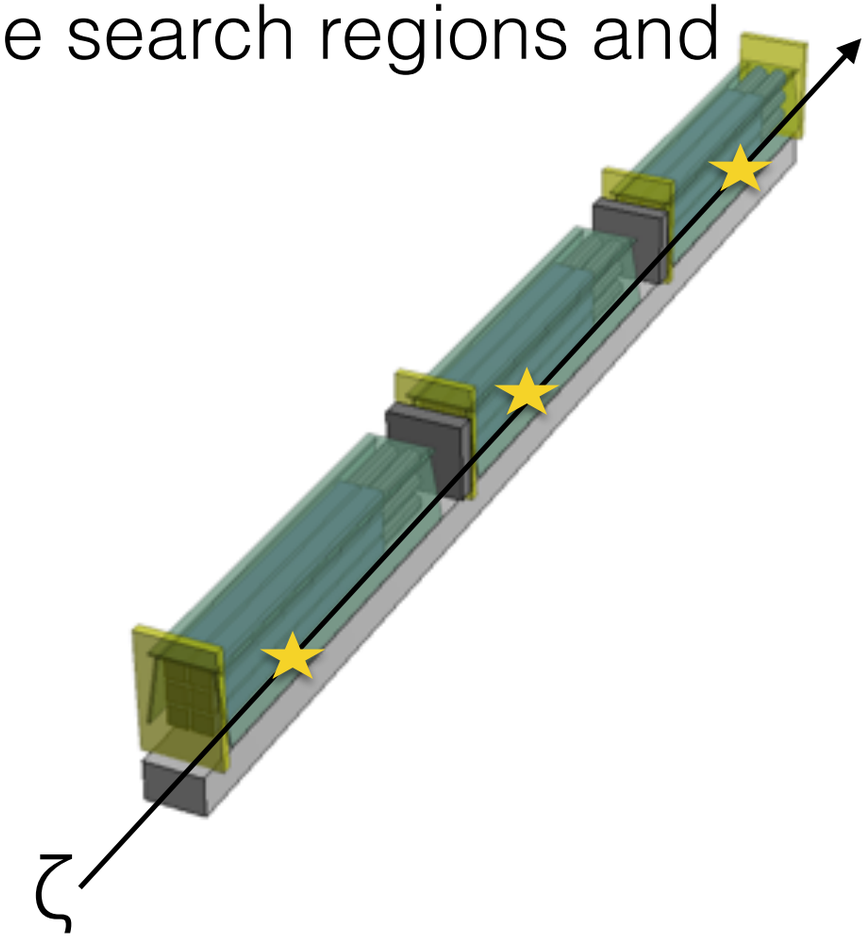


In B field can lose electrons!

Designing a search

- Detector **aligned and calibrated** - now define search regions and measure backgrounds for demonstrator

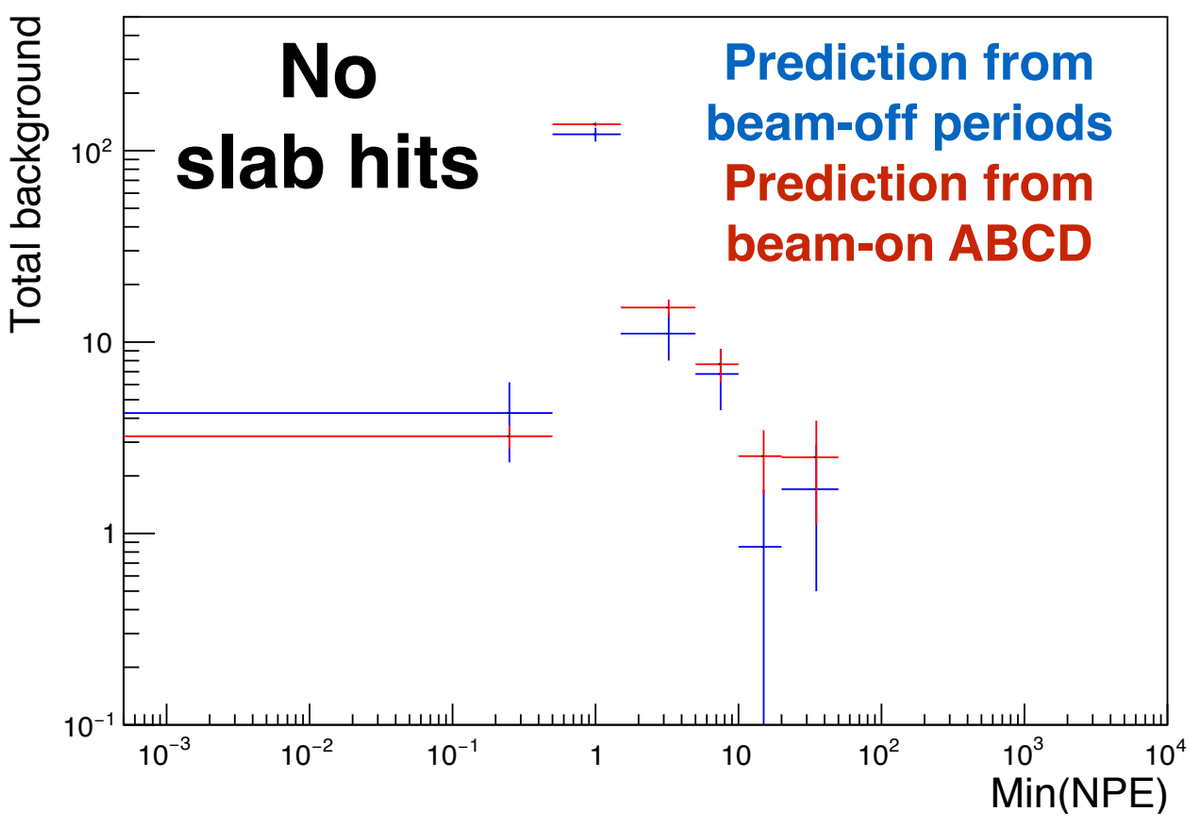
- Signal selections:
  - Single channel hit per layer
  - Pointing path in three layers
  - No activity in rest of detector
  - Max time window between layers < 15ns



- Two methods to measure backgrounds: beam-off periods and ‘ABCD’

Background measurement

- Measurement with data collected during beam-off periods consistent with 'ABCD' prediction using beam-on data
- Beam component to background subdominant (confirming in simulation now)

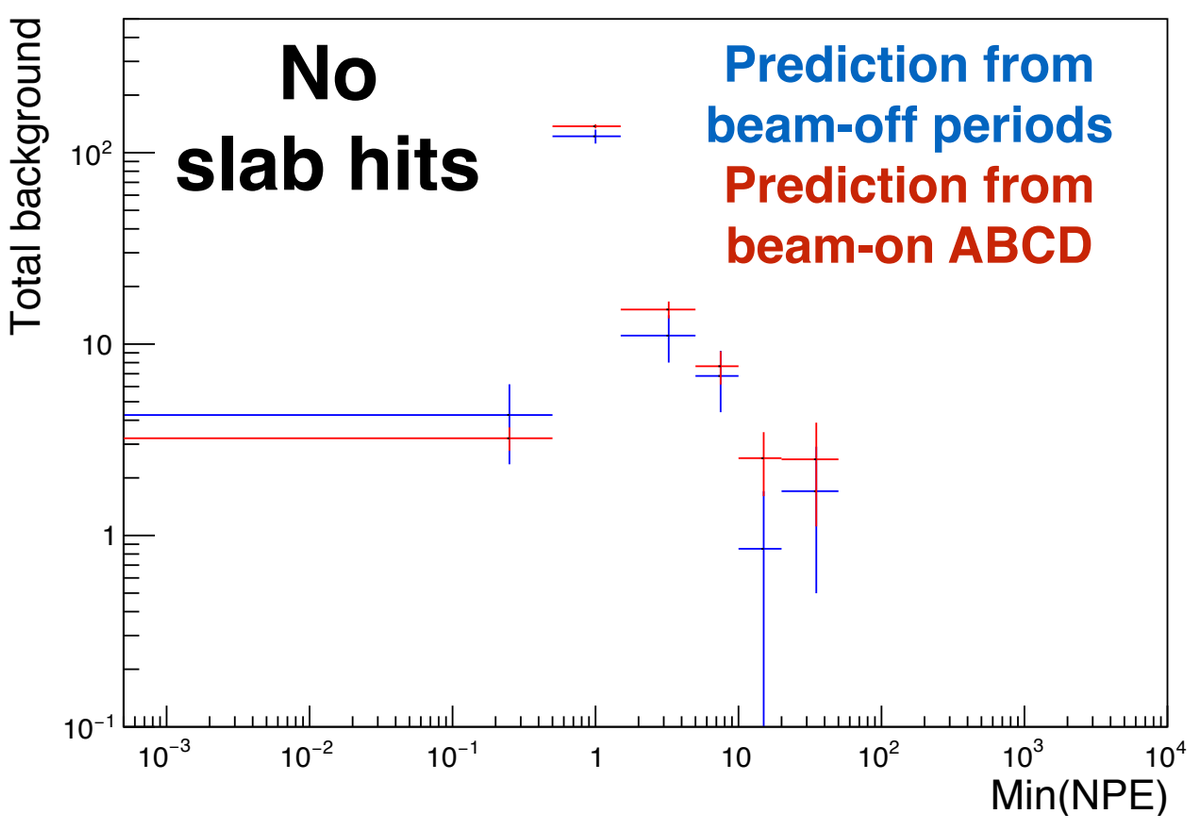


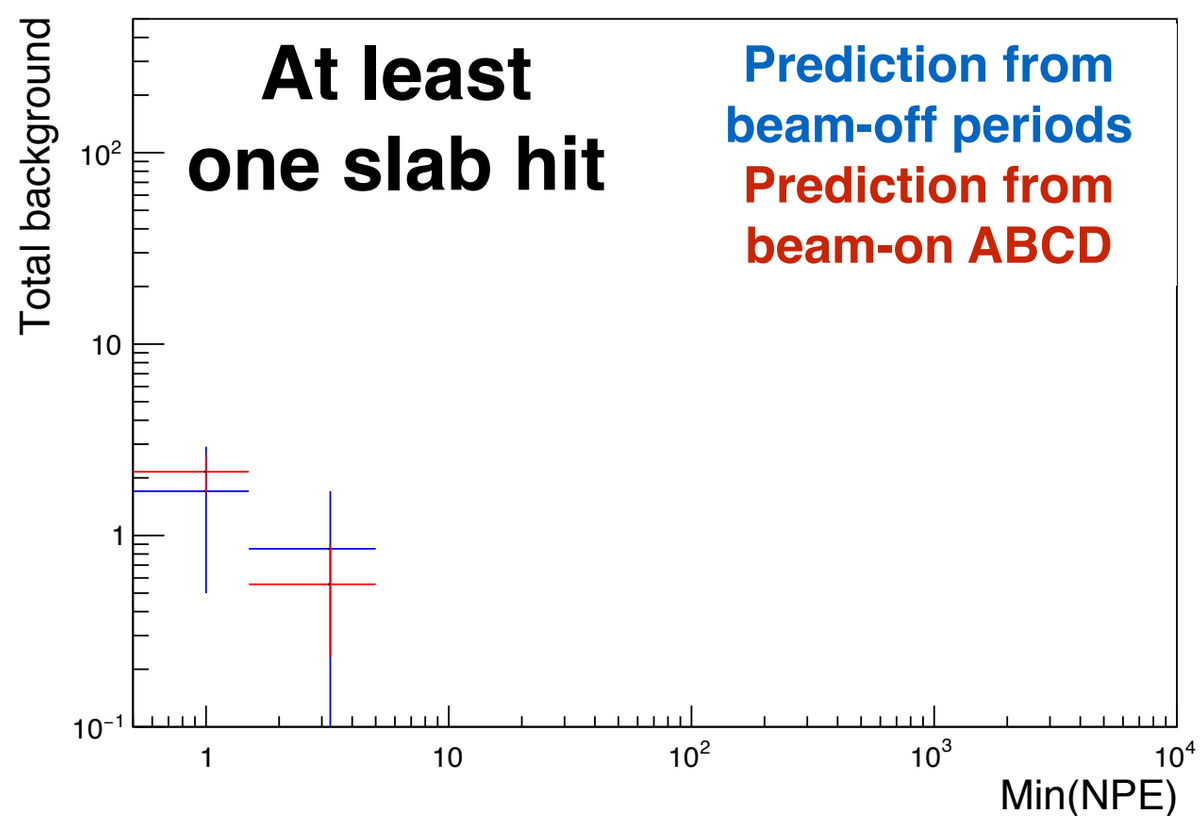
A	B
pointing path, max deltaT < 15 ns	non-pointing path, max deltaT < 15 ns
pointing path, max deltaT > 15 ns	non-pointing path, max deltaT > 15 ns
C	D

$N_{A\ (signal)} = N_B \times N_C/N_D$
(per NPE bin)

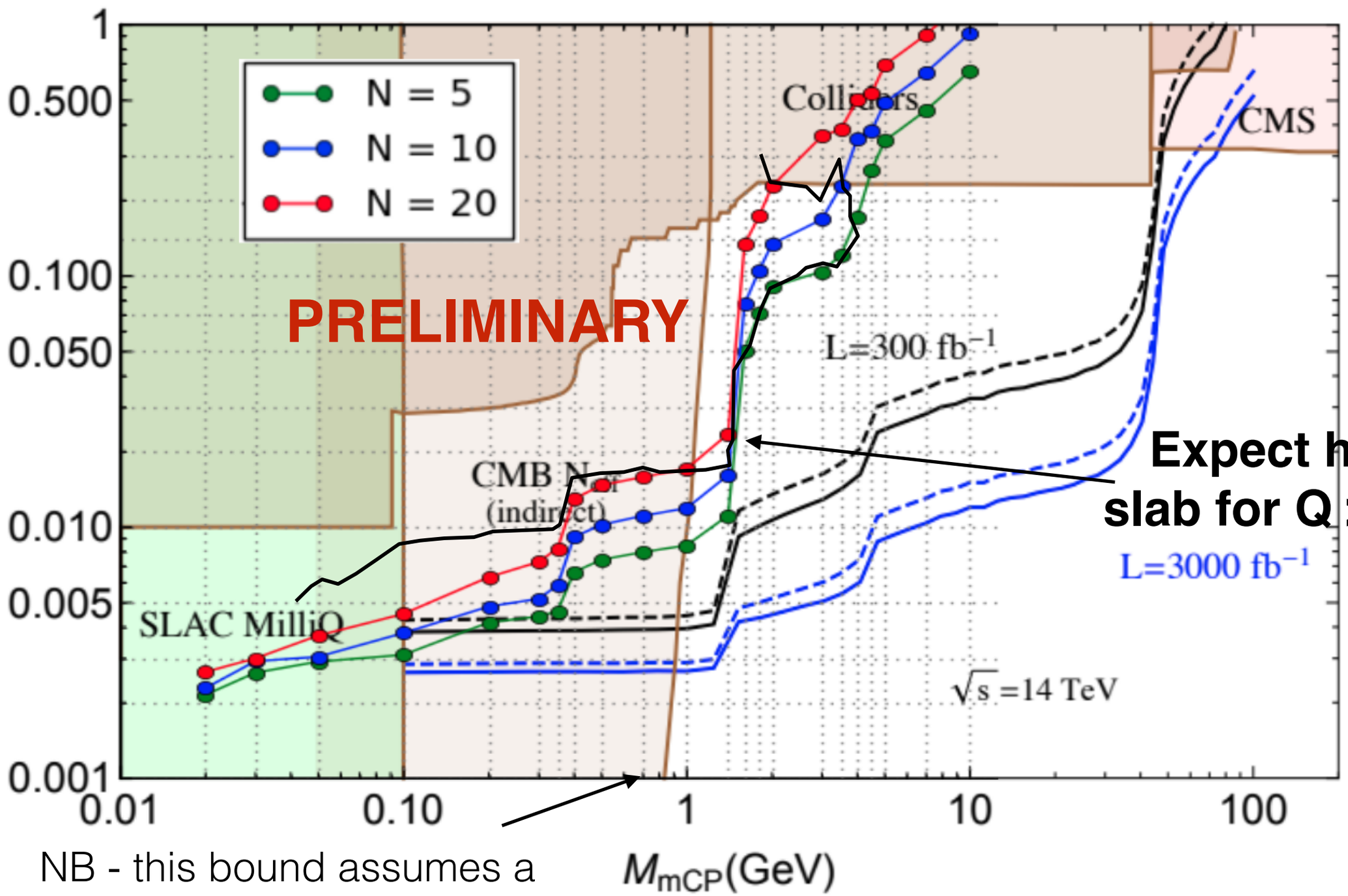
Background measurement

- Want sensitivity to wide range of charges: can also allow slab hits if signal much smaller than muon deposit
- Much smaller background! Motivates four layer design for full detector (see later!)
- Exact signal region definition/predictions being finalised





What level of sensitivity to expect?



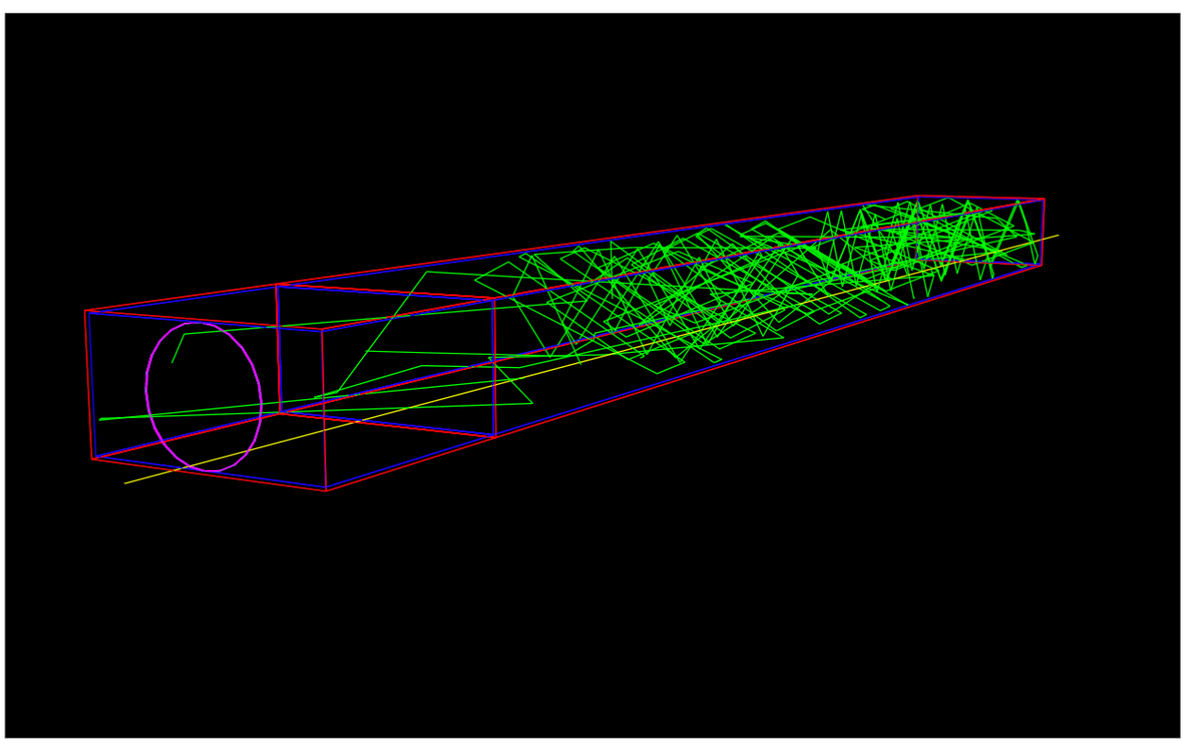
Expect hits in slab for Q > ~0.02

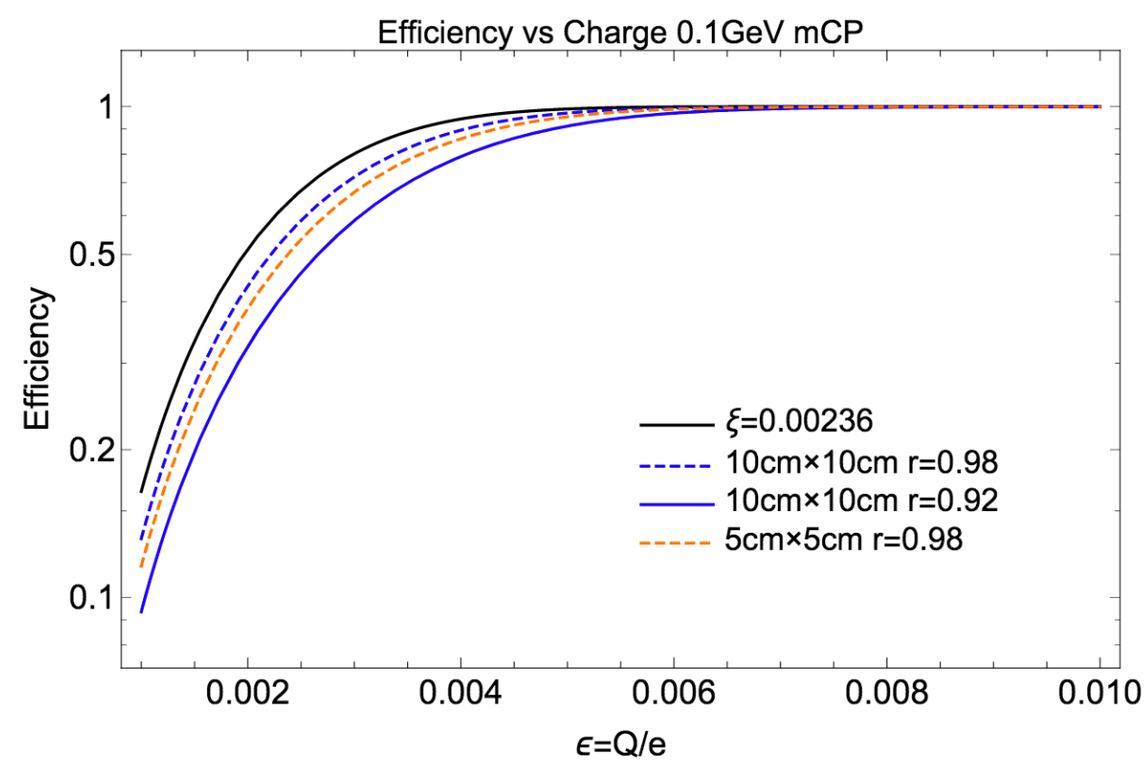
NB - this bound assumes a massless dark photon

NB: NPE not calibrated per demonstrator PMT

Detector simulation

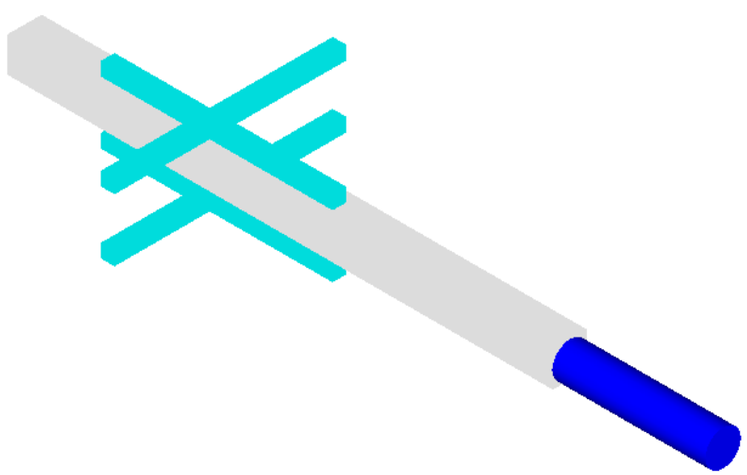
- Full GEANT simulation of milliQan demonstrator
- Models reflectivity, light attenuation length and shape of scintillator
- Input variables: PMT quantum efficiency, light emission spectrum, light yield, surface roughness, …

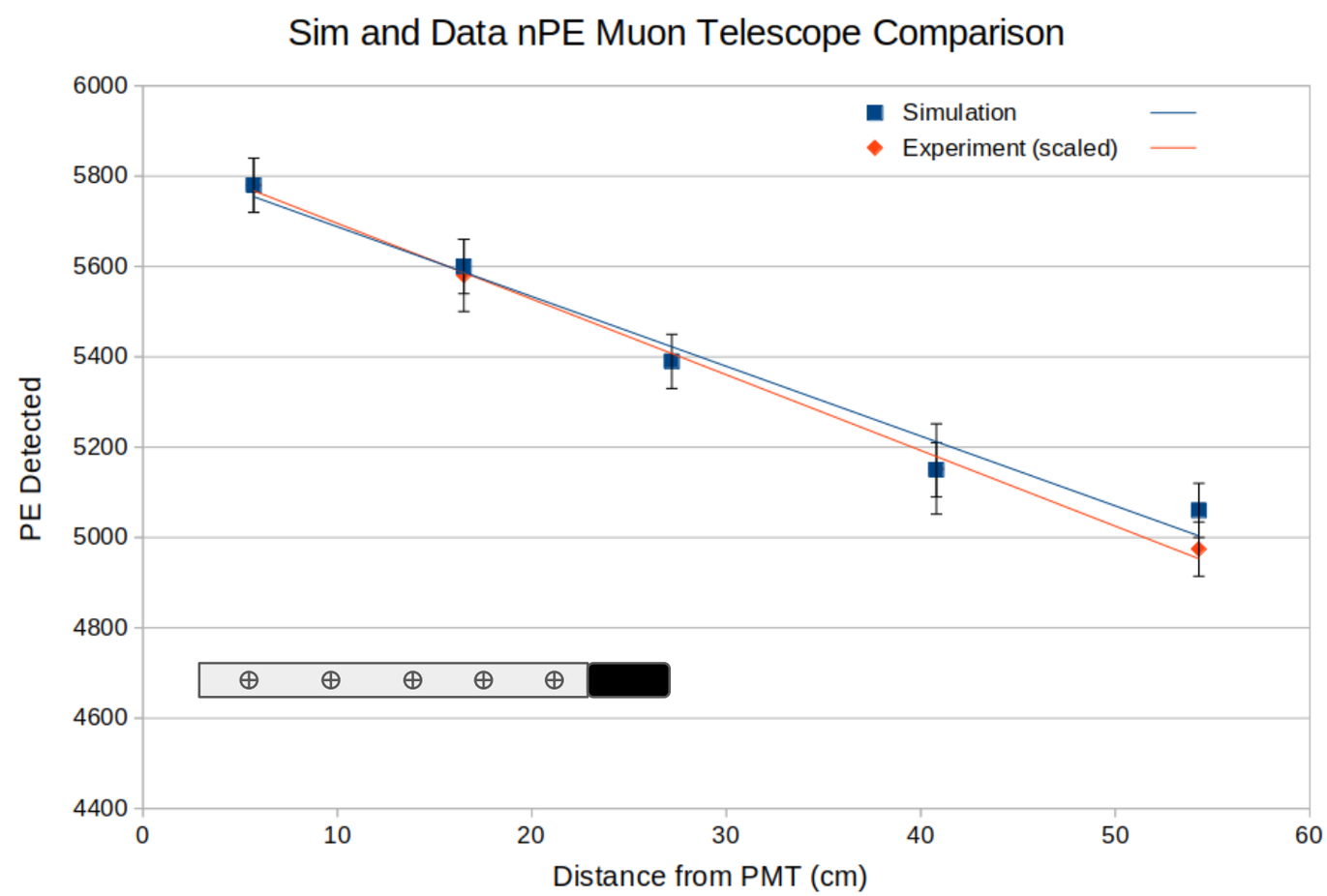




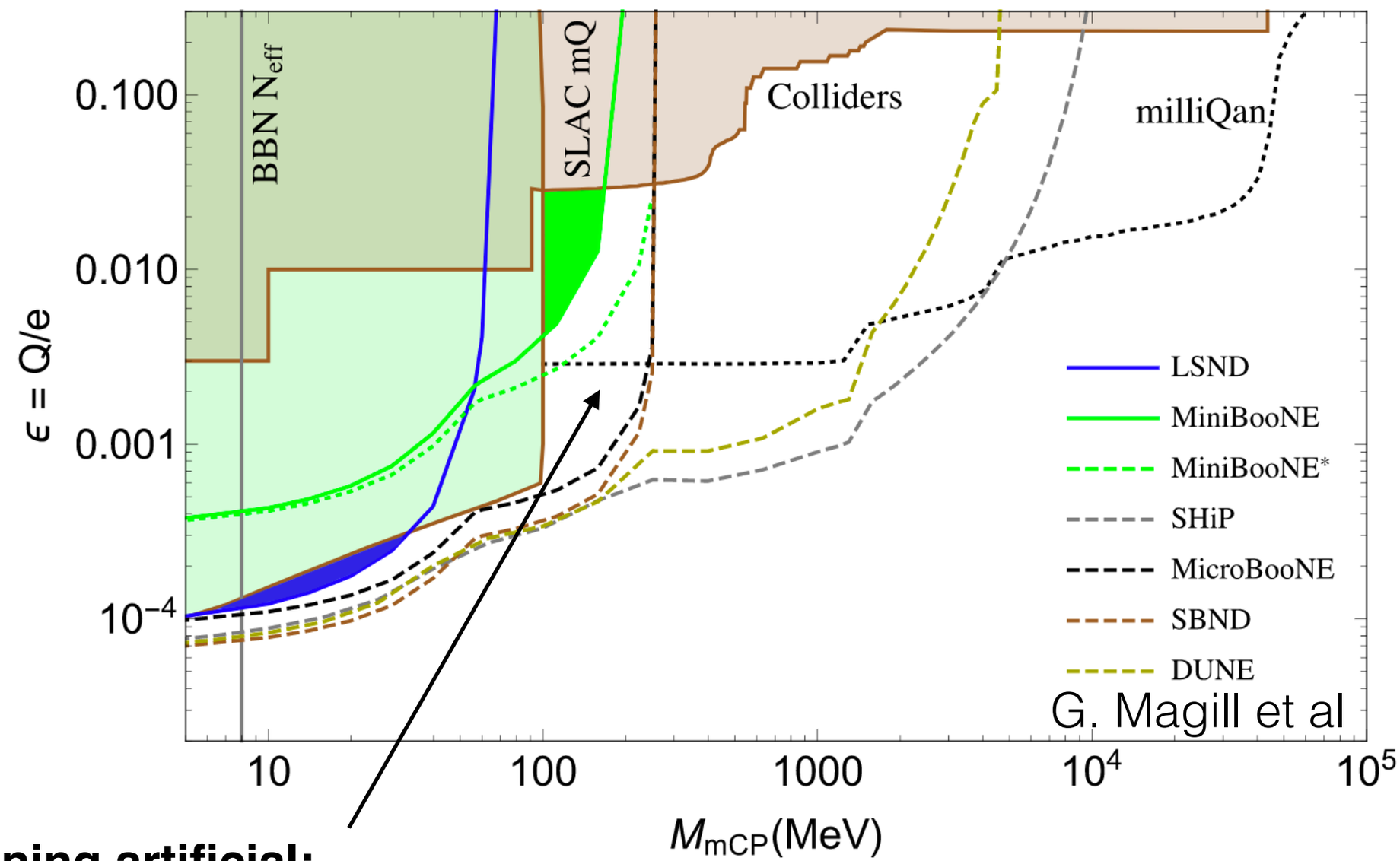
Calibrating detector simulation

- Validate detector simulation on bench using quad trigger system to assure vertically-travelling muons with specific paths through milliqan bar
- Good agreement for the effective light attenuation length of the scintillator bar
- Work-ongoing to calibrate per-PMT detection efficiency for demonstrator





Comparisons (from pheno paper)



flattening artificial:
no mCP production from QCD/ hadronic processes included (only DY/prompt resonances)!

Attracting interest in the theory community!

arxiv1806.03310