UNIVERSITY OF CALIFORNIA · SANTA BARBARA

THE MILLIQAN EXPERIMENT

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**

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No sign of new physics at the LHC

Basic structure of hidden sector models:

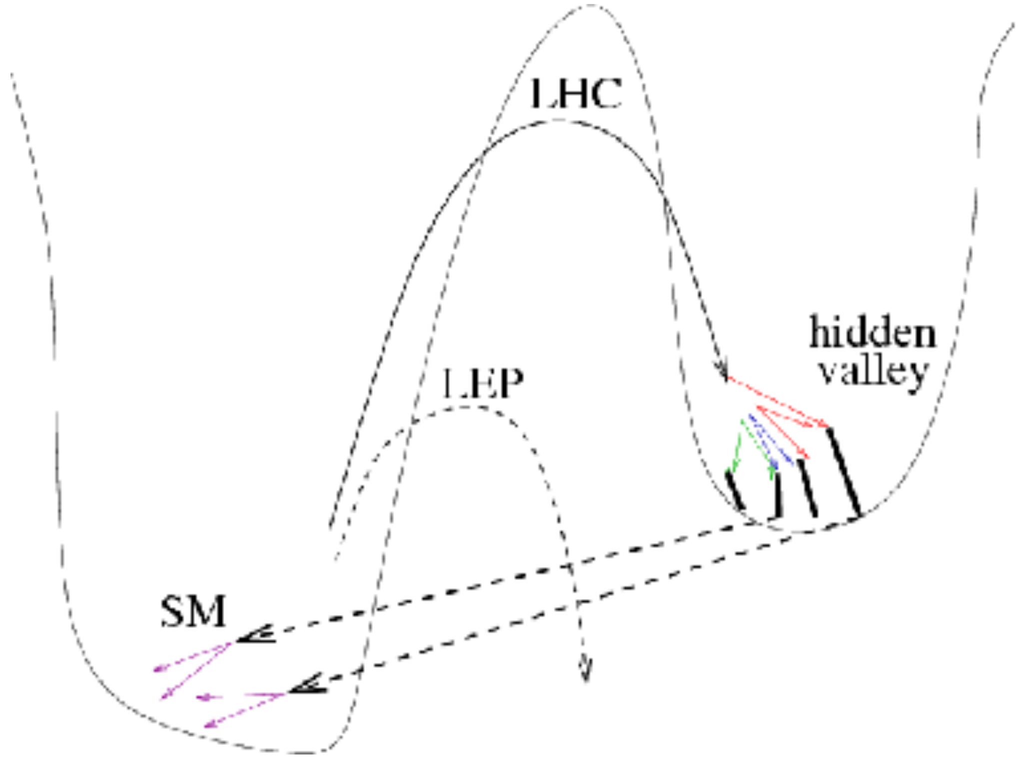
Standard model

communicator

Hidden sector (including stable DM particles)

Hidden sector separated by heavy mediator or **low couplings**

Zurek, Strassler

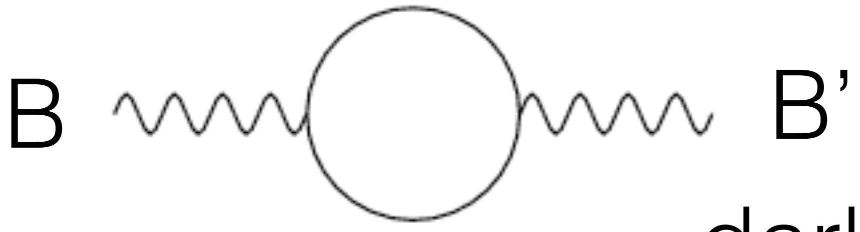


Why milli-charged?

Consider a model with kinetic mixing with a new 'dark' boson **- link to the dark/hidden sector**

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

introduces mixing



SM

dark sector

massless U'(1) boson in the dark sector

'dark EM'

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

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

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Why milli-charged?

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

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

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

Removes mixing term and generates hypercharge for new fermion

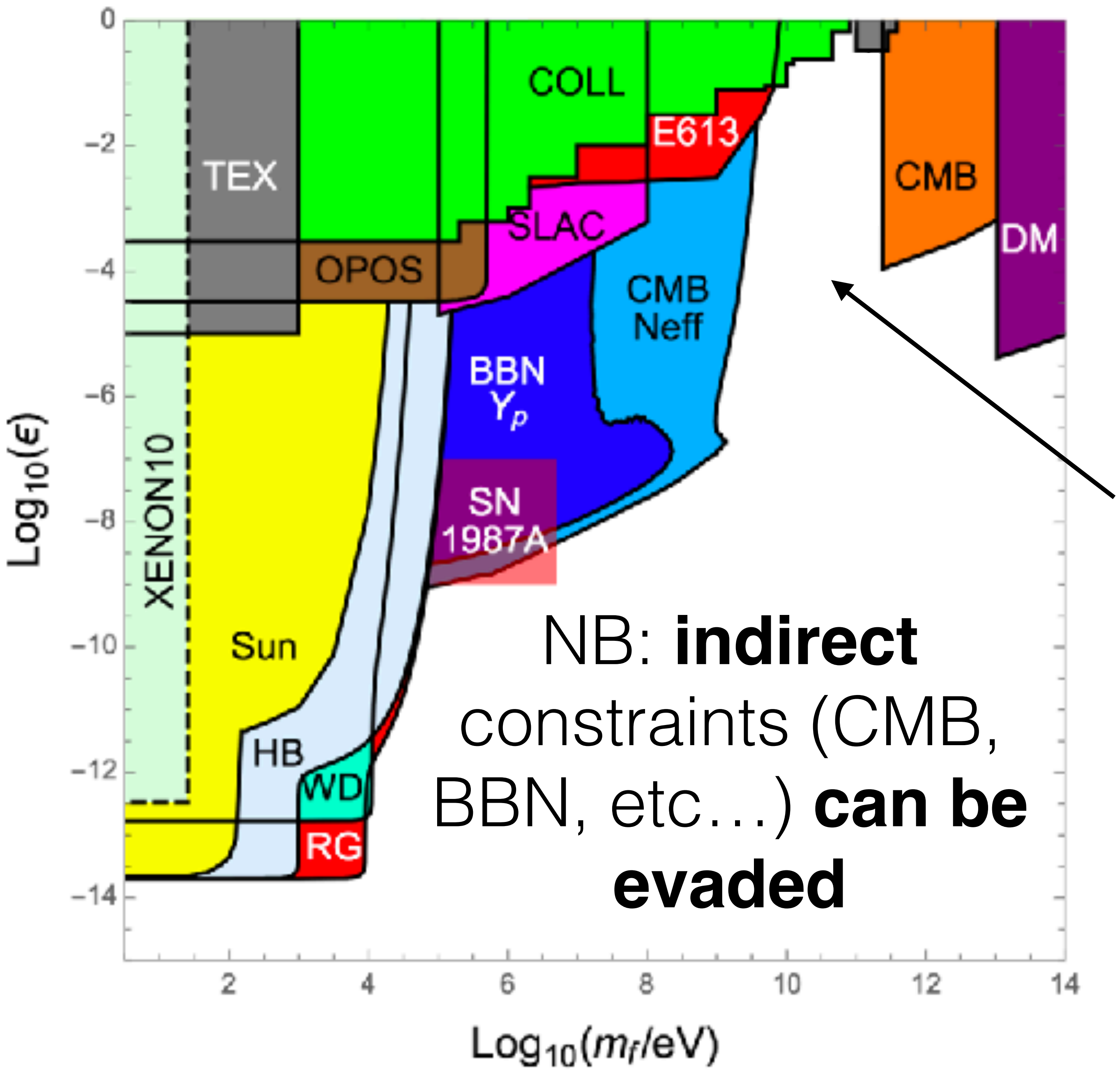
$$\mathscr{L} = \mathscr{L}_{SM} - \frac{1}{4} B'_{\mu\nu} B'^{\mu\nu} + i\overline{\psi}(\partial + \underbrace{i\kappa e'B} + ie'B' + iM_{mCP})\psi$$

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

Searching for millicharged particles

$Q = \epsilon e$

CMS



NB: **indirect** constraints (CMB, BBN, etc…) **can be evaded**

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

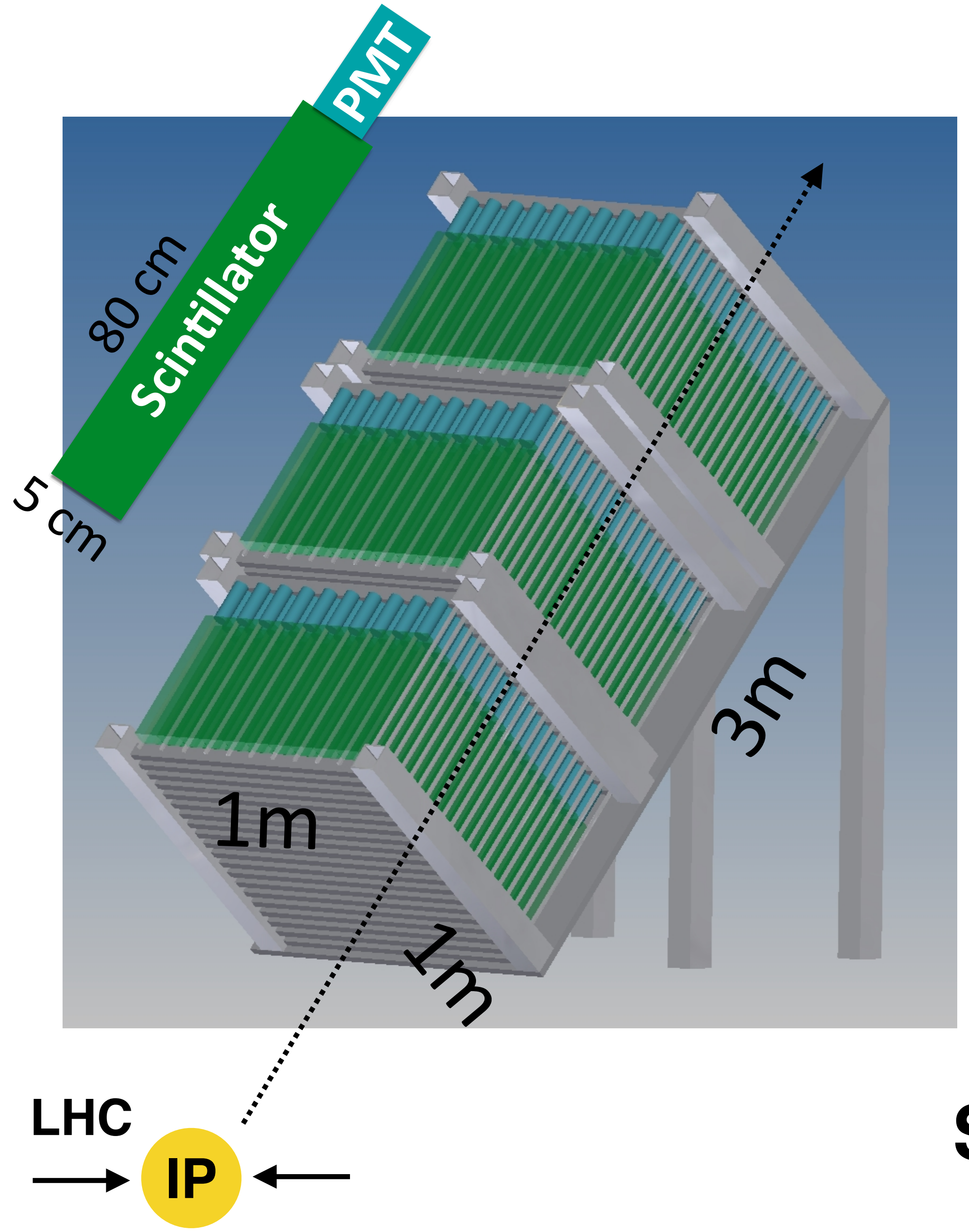
general purpose LHC detectors insensitive (**dE/dx ~ Q²**)

→ target with **milliQan**!

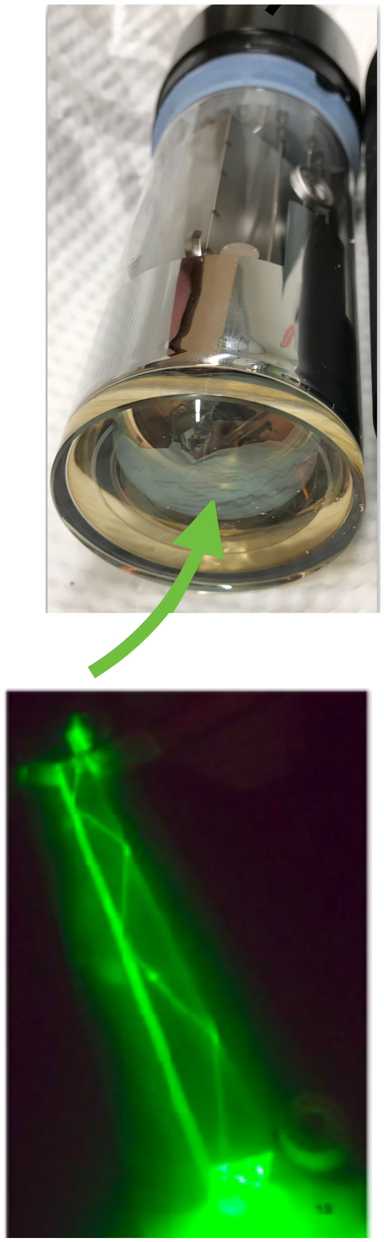
arXiv:1511.01122

Searching for milli-charged particles at the LHC

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
- Expected signal: few scintillation photons in multiple layers
- Each bar + PMT must be capable of detecting a single scintillation photon
- Control backgrounds: signal in each layer within small (~15 ns) time window and that points towards the IP
- Modular design is easy to scale and adapt!

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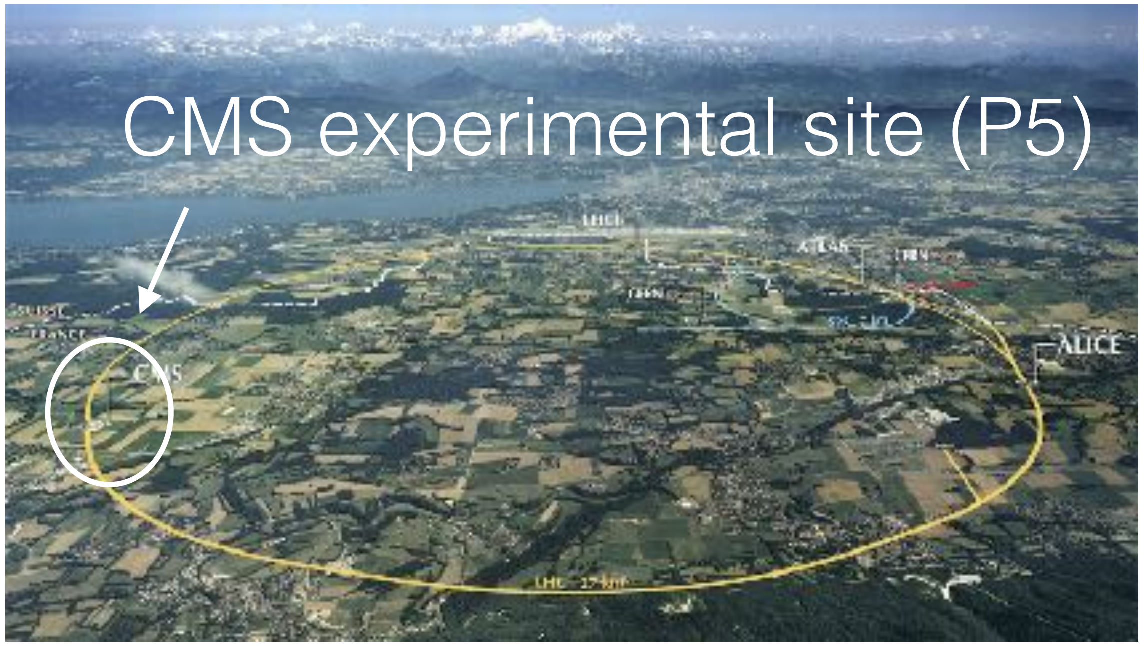
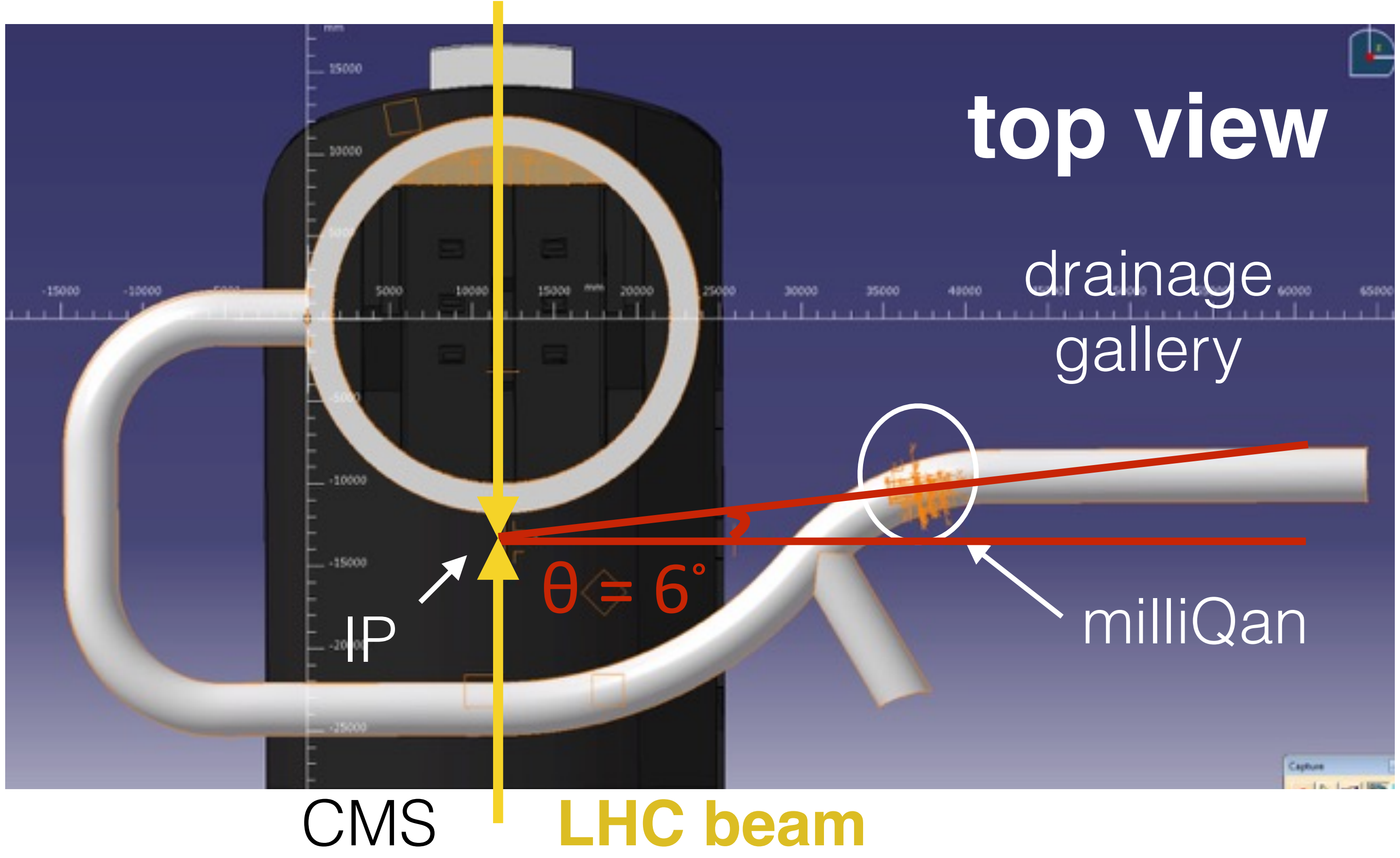
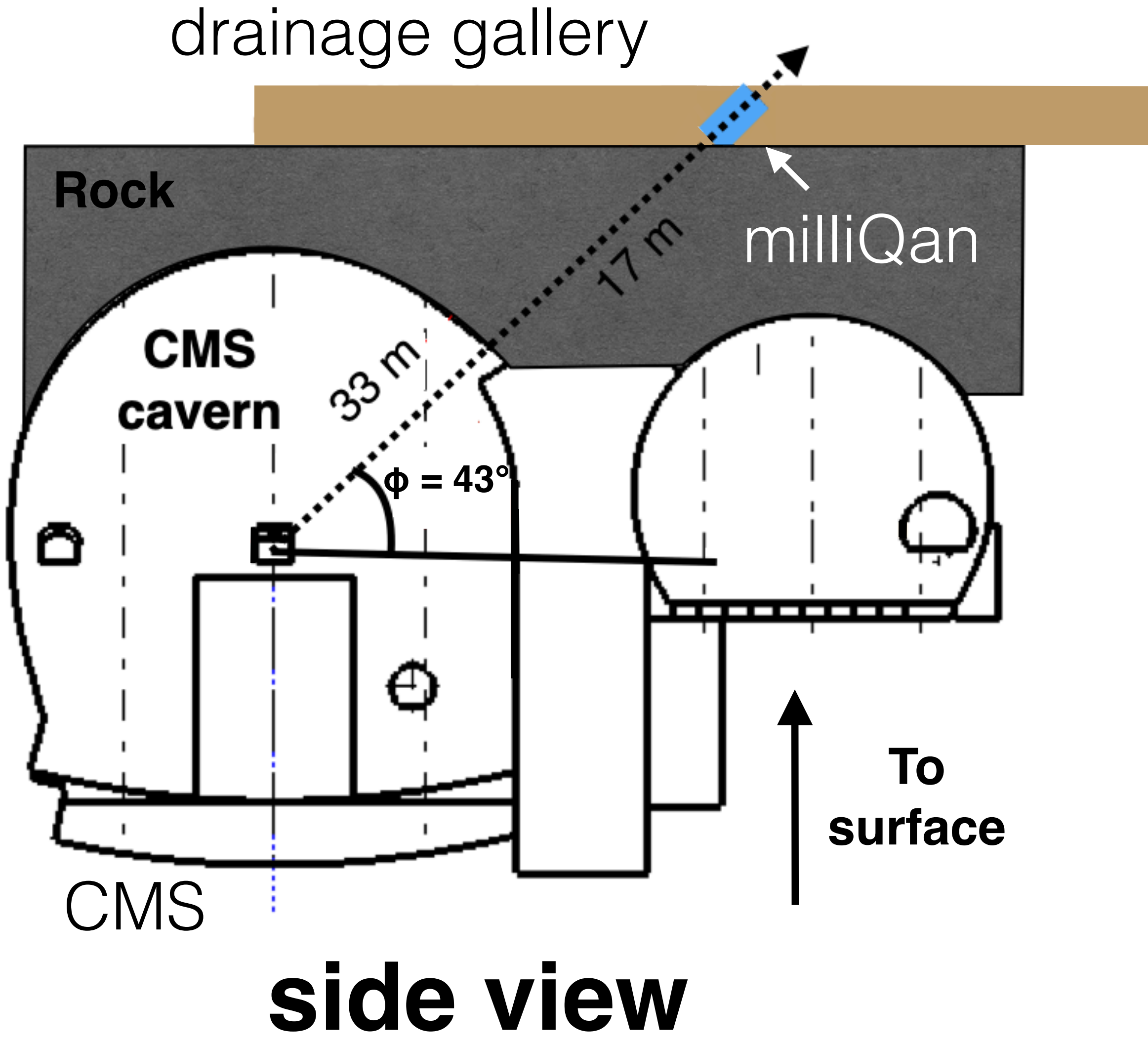
Proposed location

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





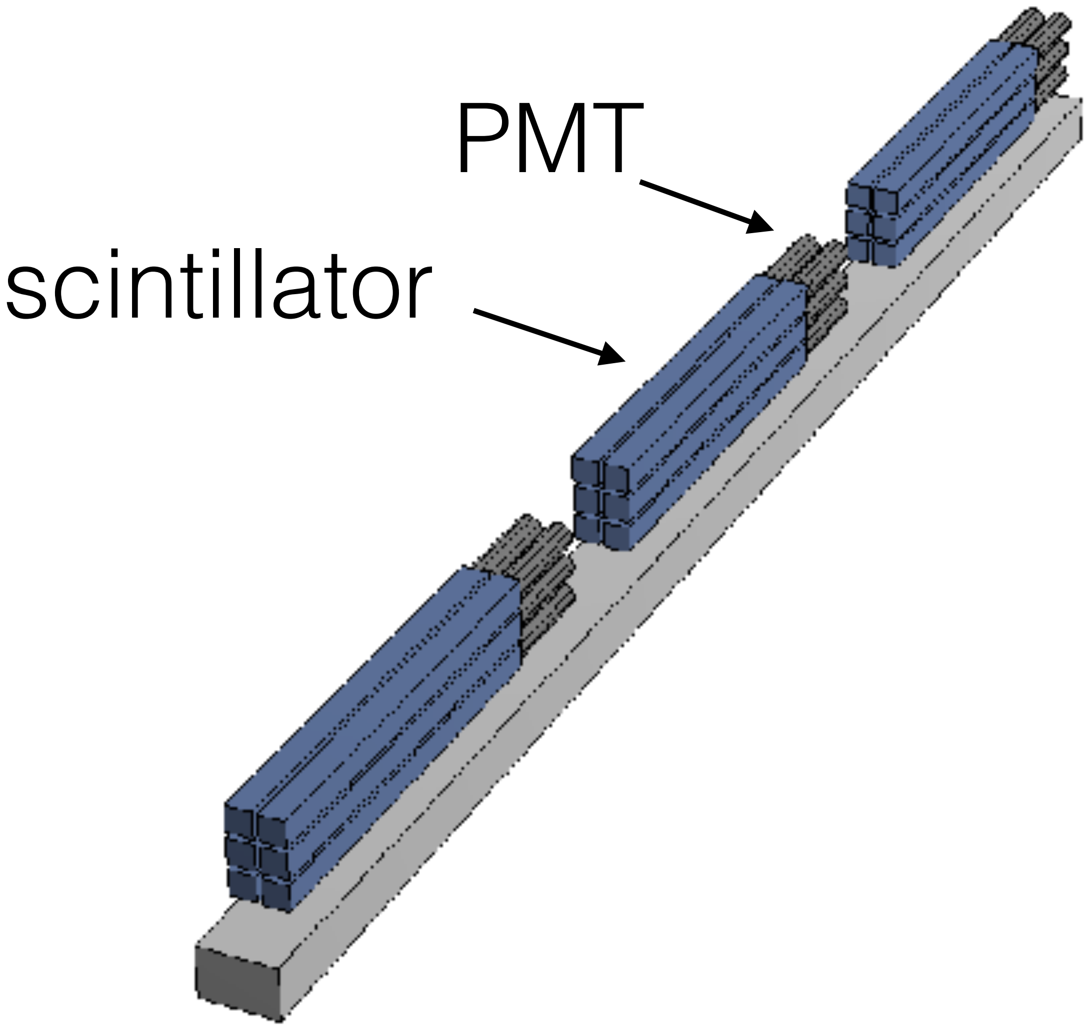


Proposed location

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

IP

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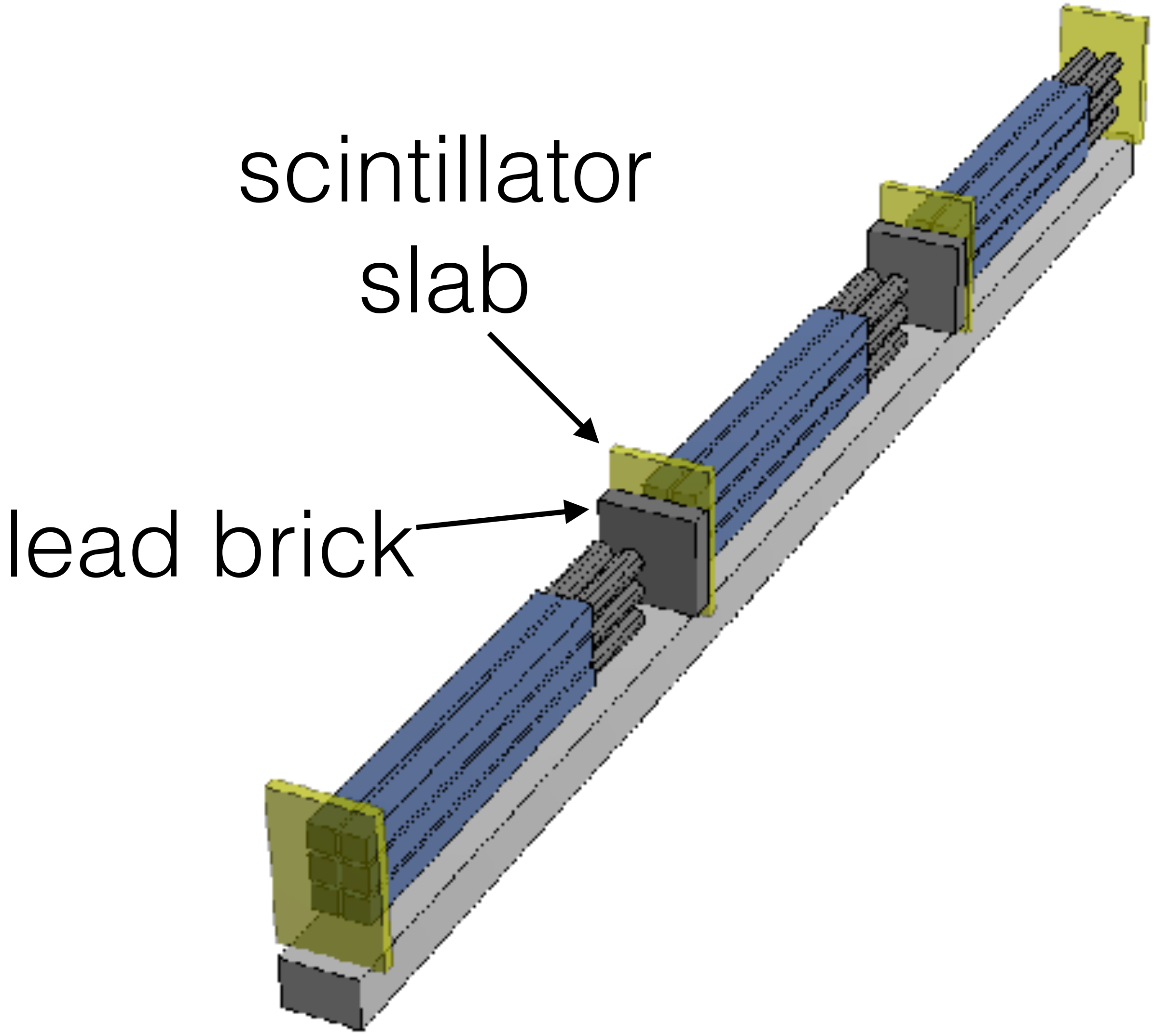
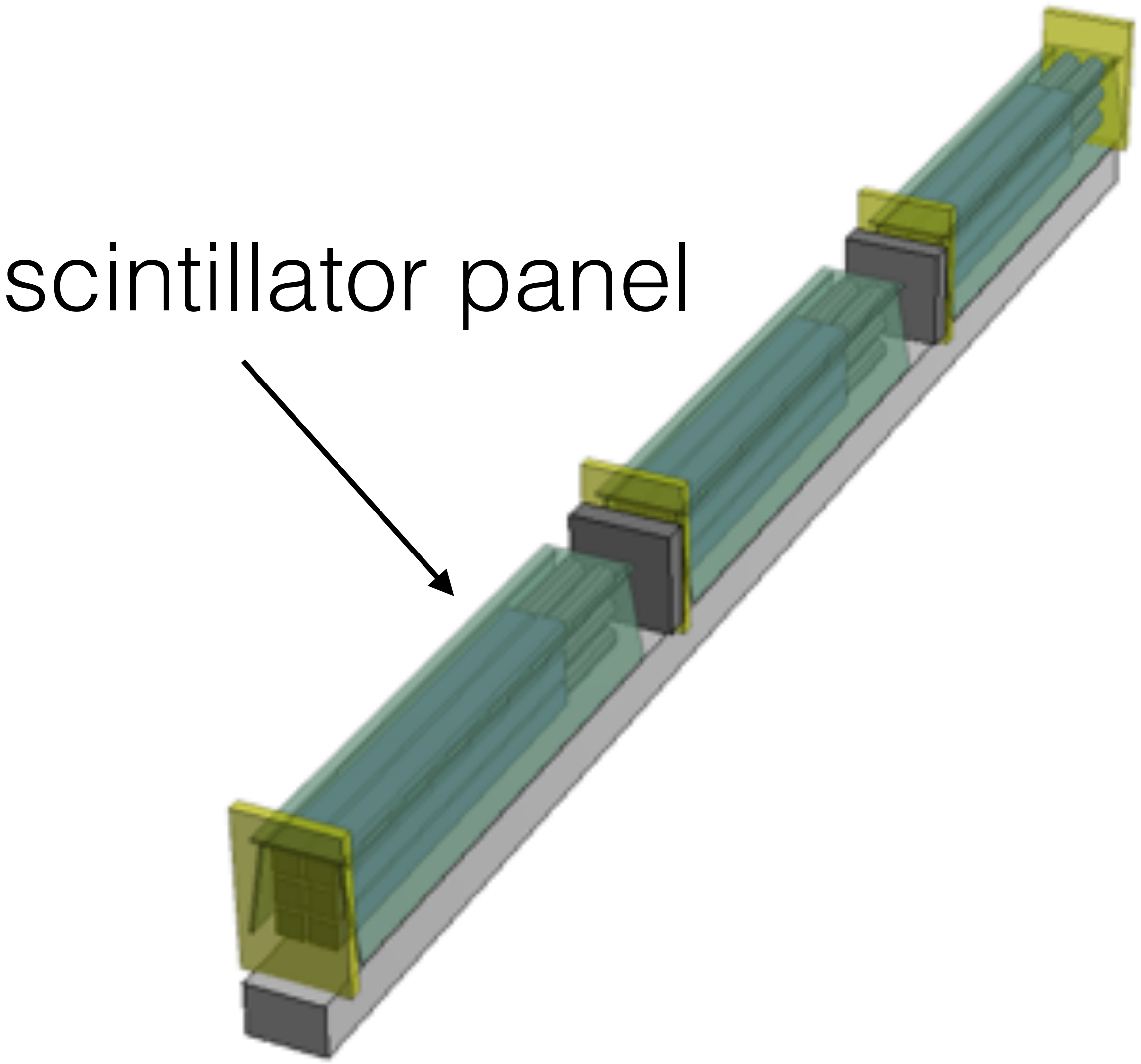
Demonstrator components



- 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
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- Scintillator slabs and lead bricks
  - Tag thru-going particles, shield radiation
- Scintillator panels to cover top + sides
  - Tag/reject cosmic muons + secondaries

IP

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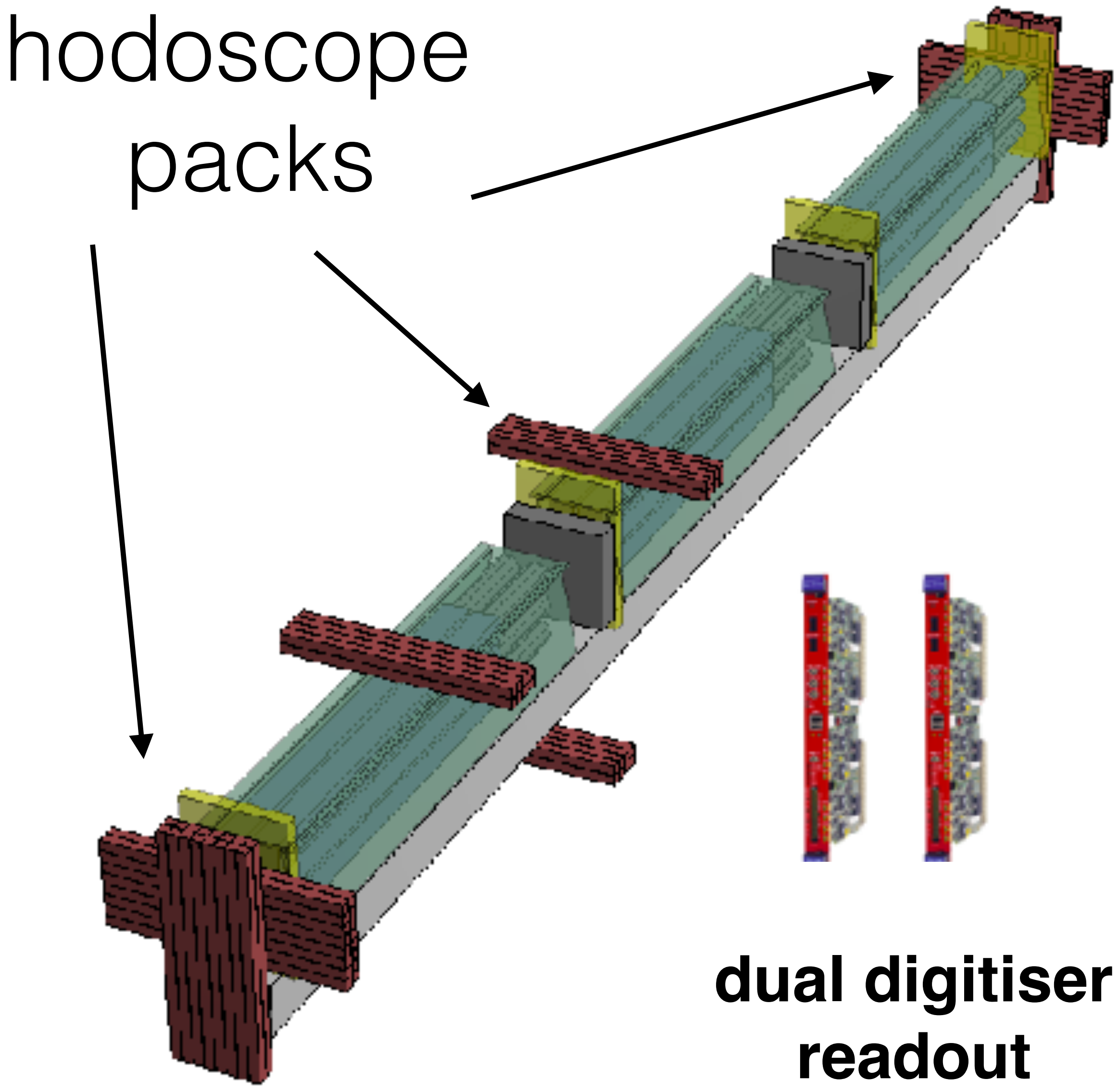
Demonstrator components



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

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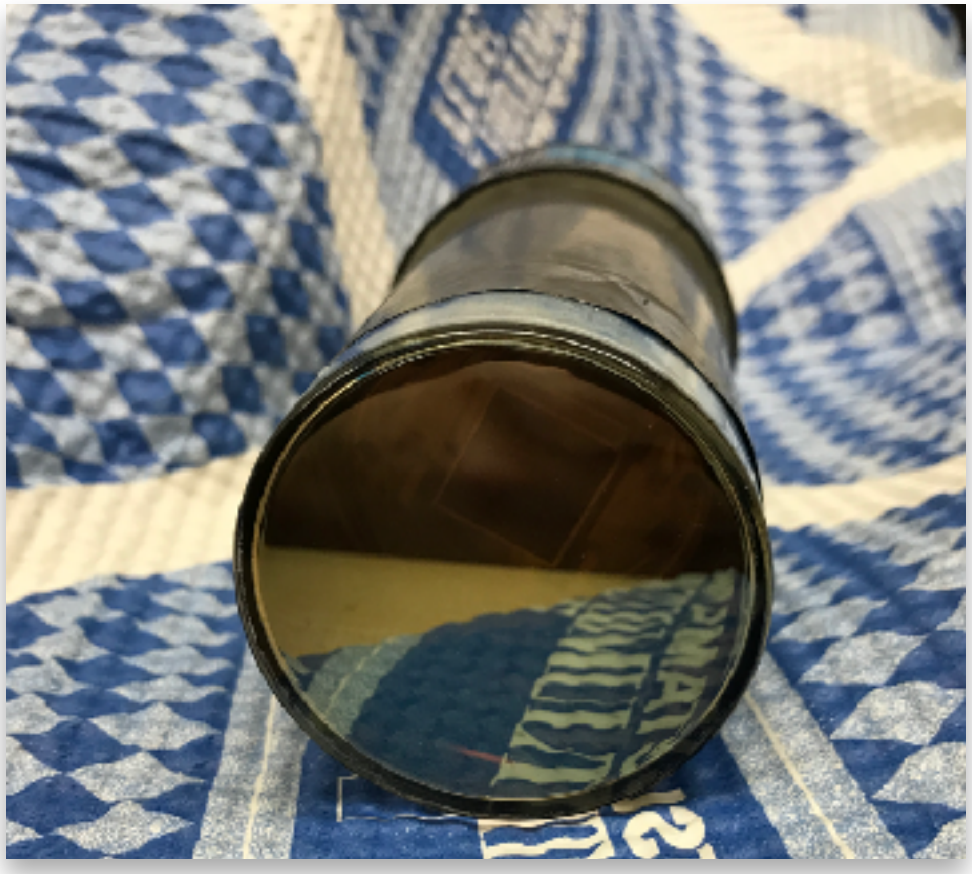
PMTs

High gain and fast
(but expensive)

Older/slower but free
(taken from older experiment)



**Hamamatsu
R7725**

**Electron Tube
9814B**

**Hamamatsu
R878**

Important lesson from demonstrator
- R878 PMTs well suited for milliQan!

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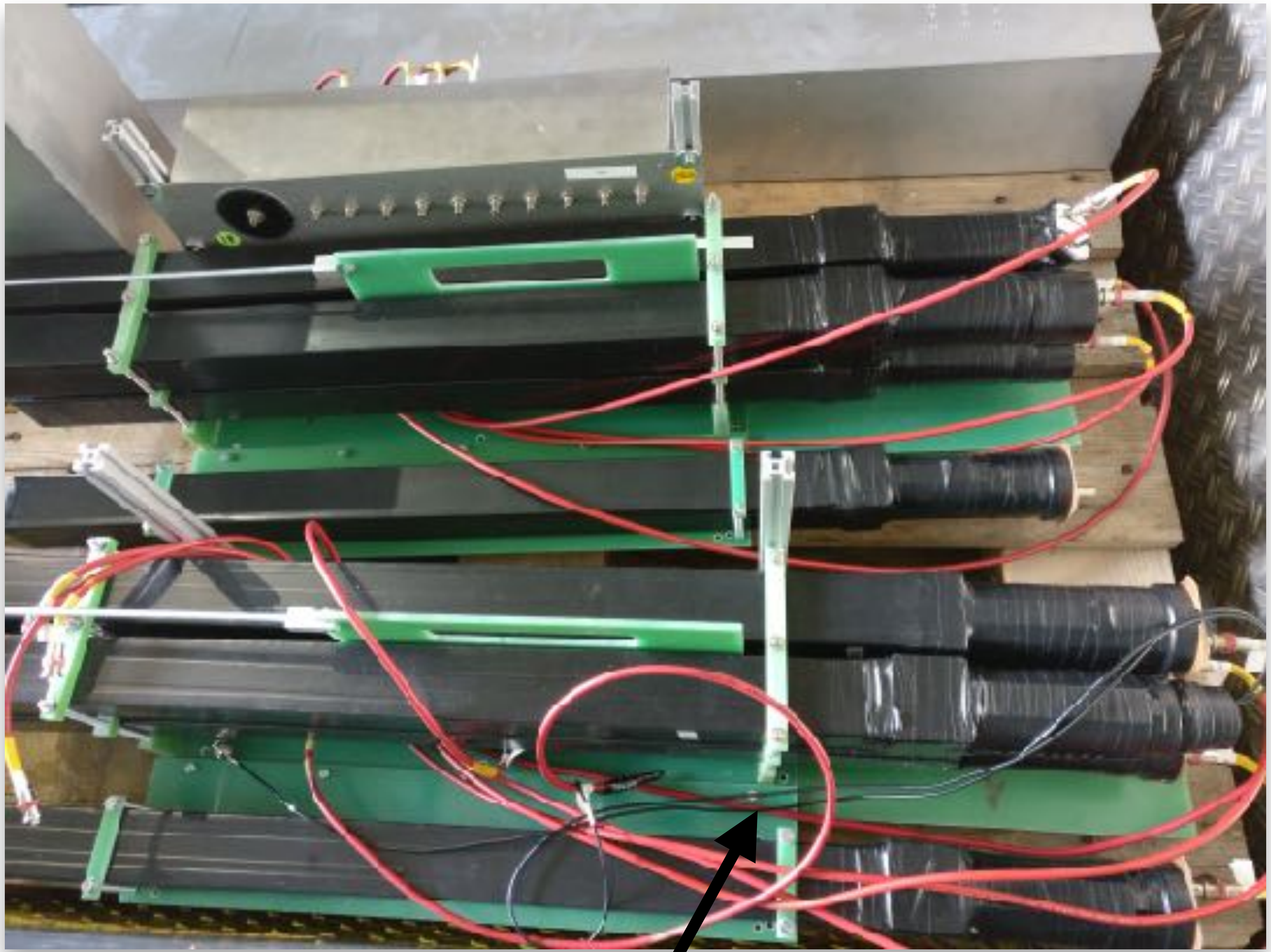
Module assembly

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



3D printed PMT casing

Fibre glass mounts for each layer

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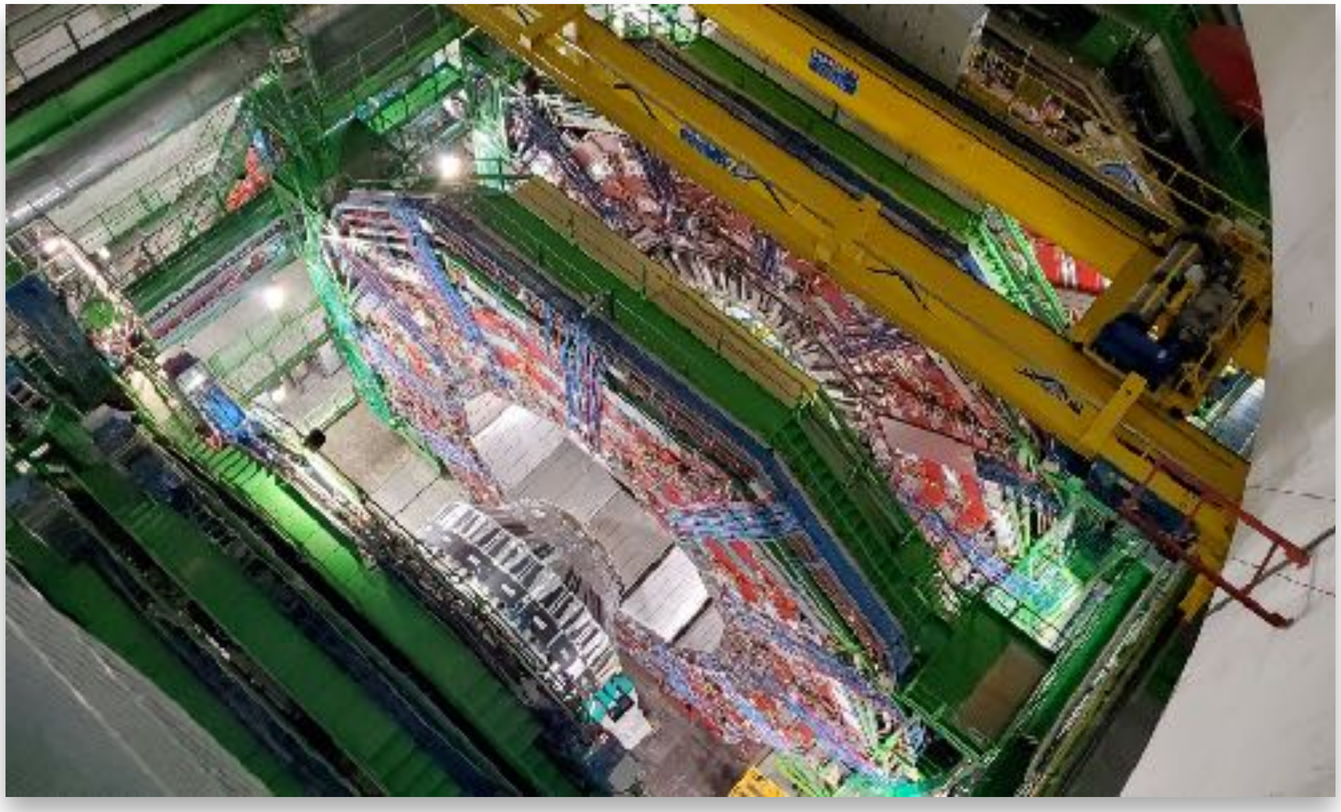
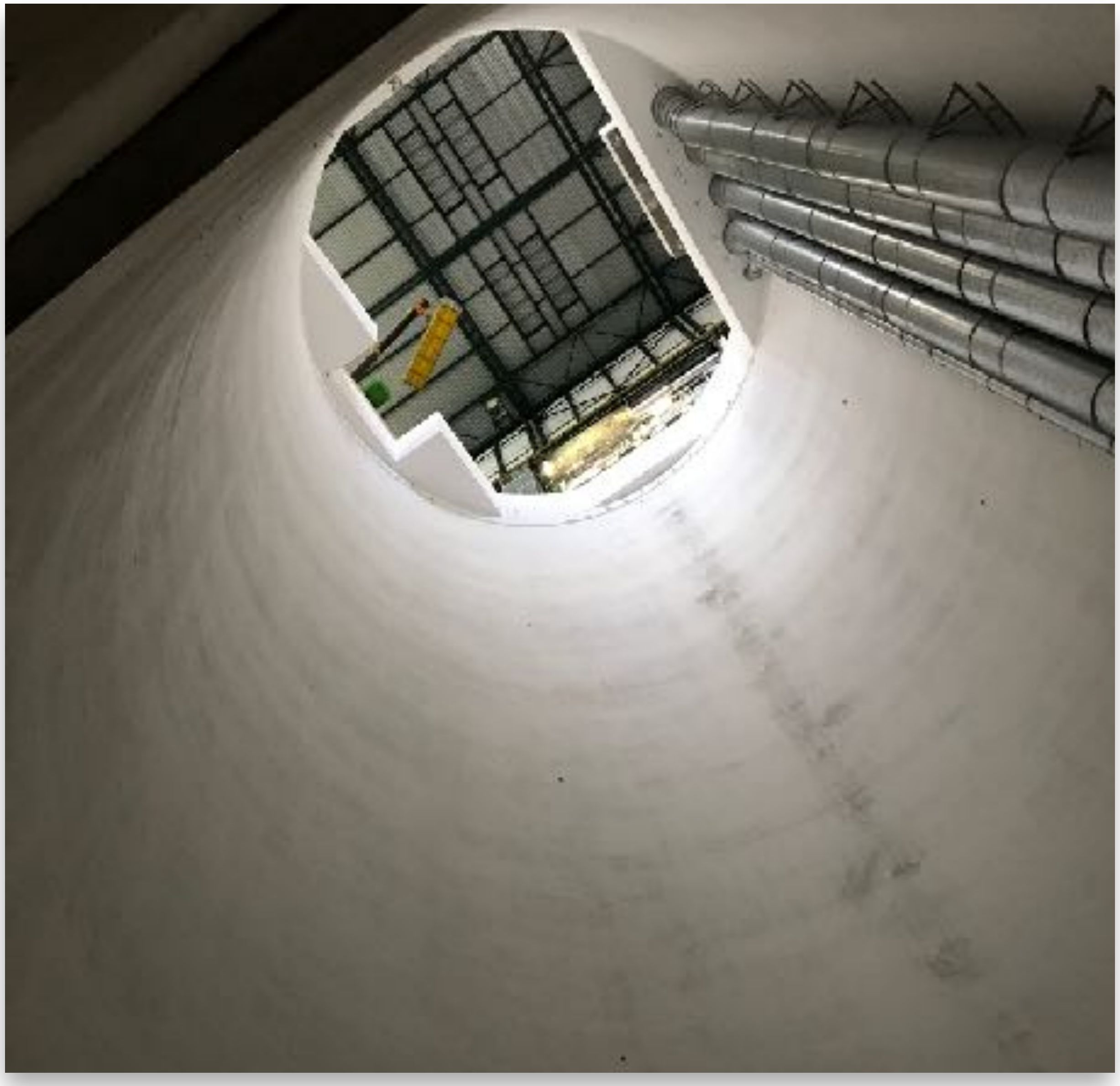
Going underground (via the CMS shaft)

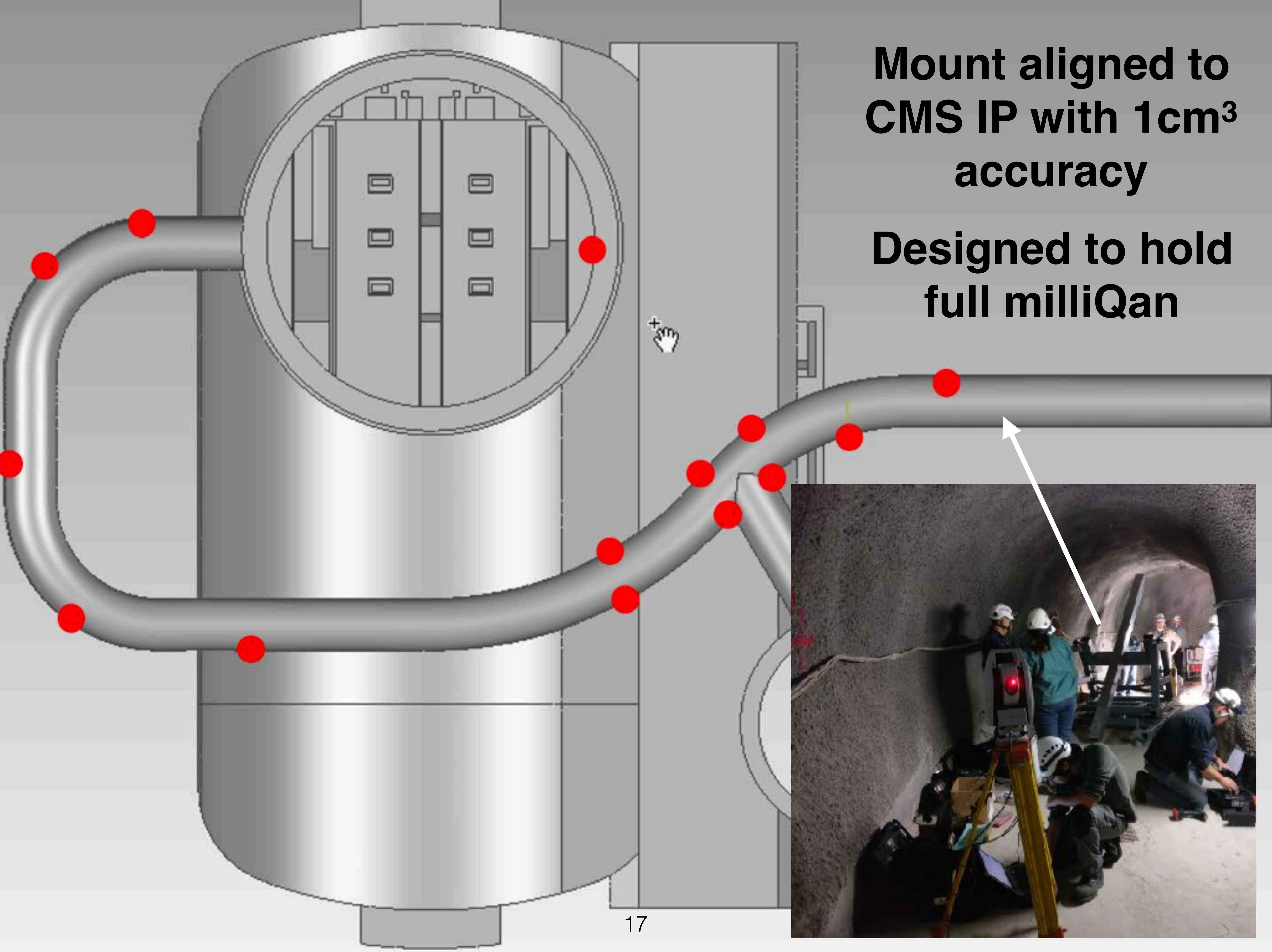




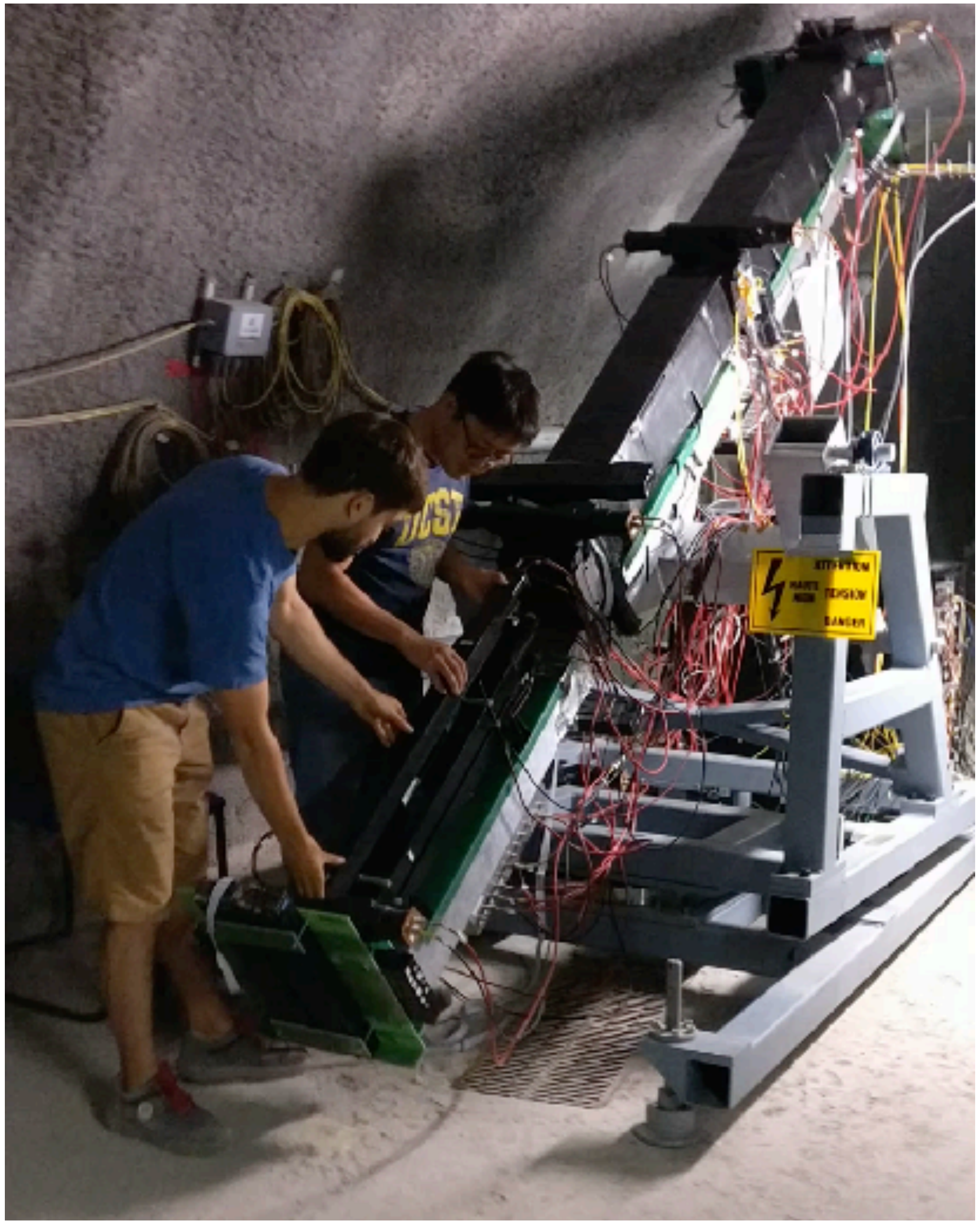
Modules assembled on the surface and then lowered to gallery

Mount aligned to CMS IP with 1cm^3 accuracy

Designed to hold full milliQan



Demonstrator



Installed on mount designed to hold full detector

- Ran very successfully, collecting **37.5 fb^{-1}**, **2000h** of data in 2018
- Operational experience in difficult environment: triggering/DAQ/DQM
- Used for range of studies to prove feasibility and provide crucial insight for full detector
- Key results: **alignment**, **calibrations**, **background measurements**
- Fully simulated in GEANT4
- **First search** for millicharged particles at a hadron collider!

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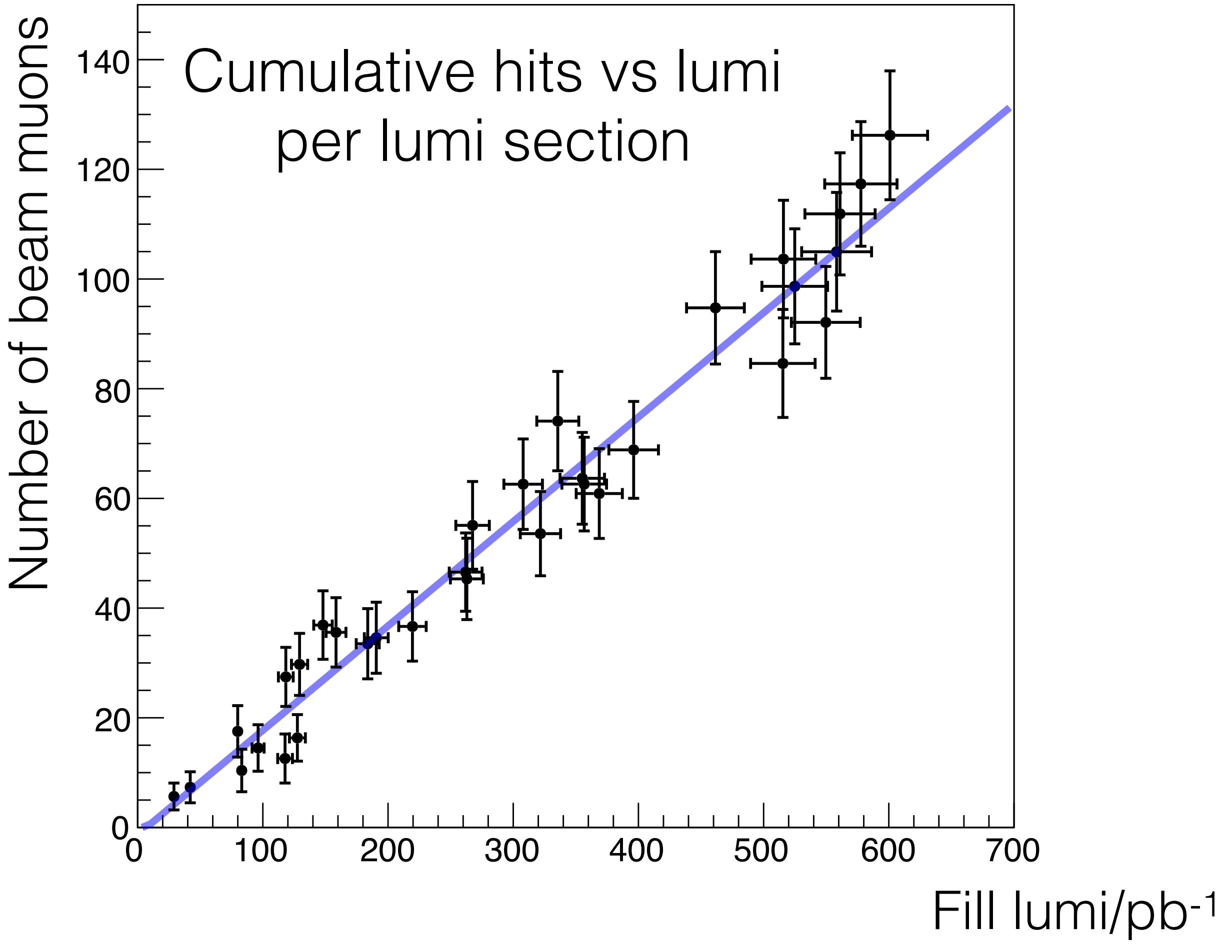
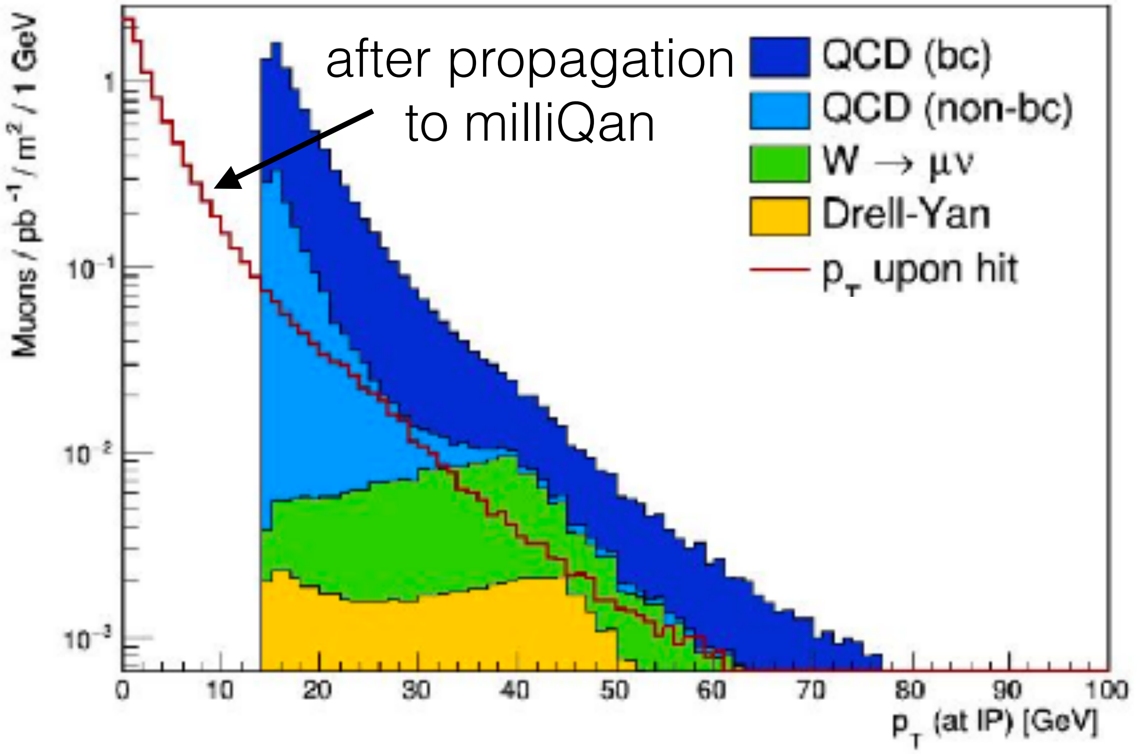
Alignment

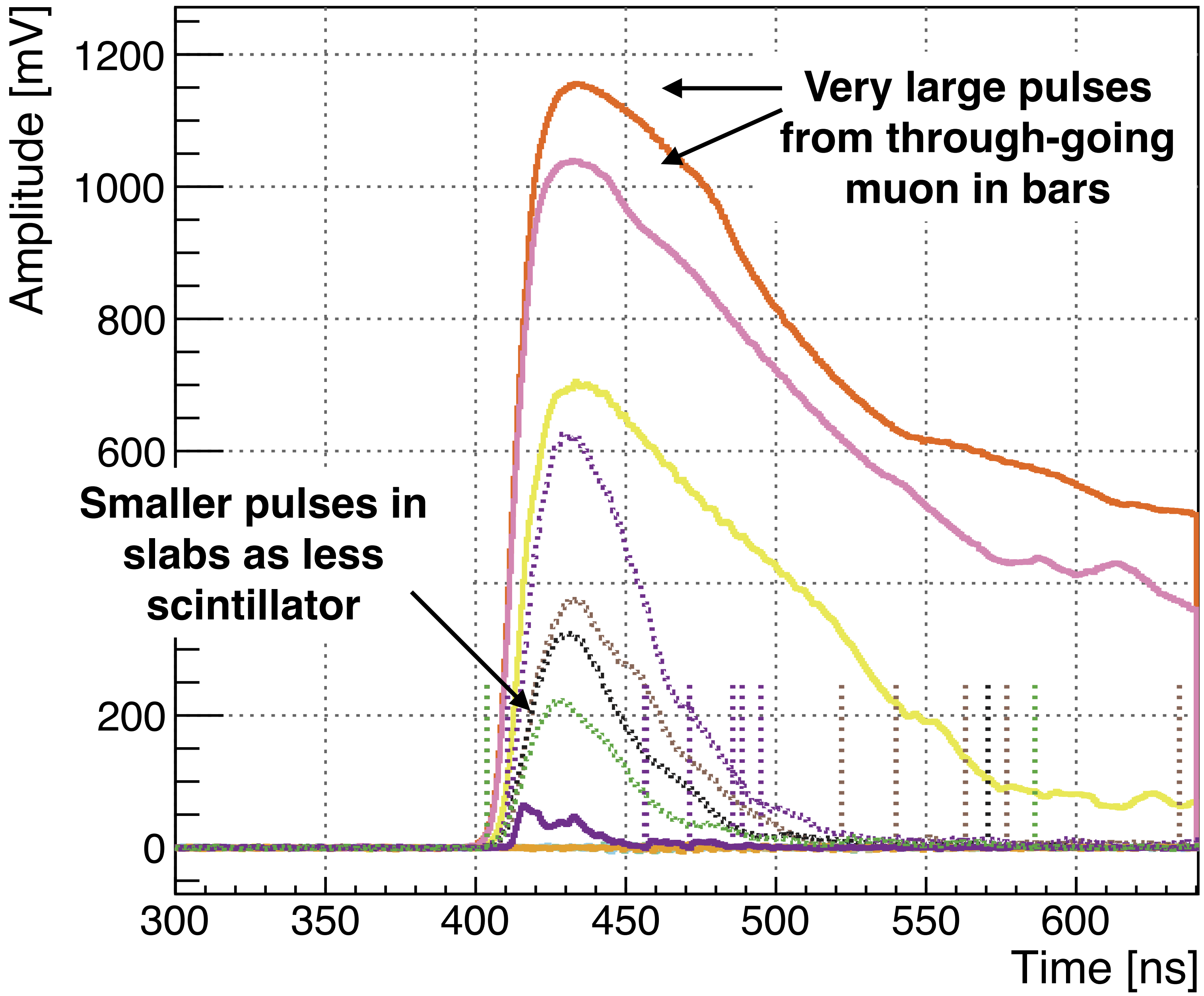
- milliQan ‘sees’ muons from the CMS interaction point
- Check occupancy agreement with expectation
  - Simulate muon production at CMS interaction point
  - Propagate through CMS material and 17 m of rock considering **multiple scattering** and **CMS magnetic field**
- Measured rate **0.20 ± 0.01/pb^{-1}** agrees well with expected **0.25 ± 0.08/pb^{-1}**
- Also validate angular spread of beam muons (see backup)





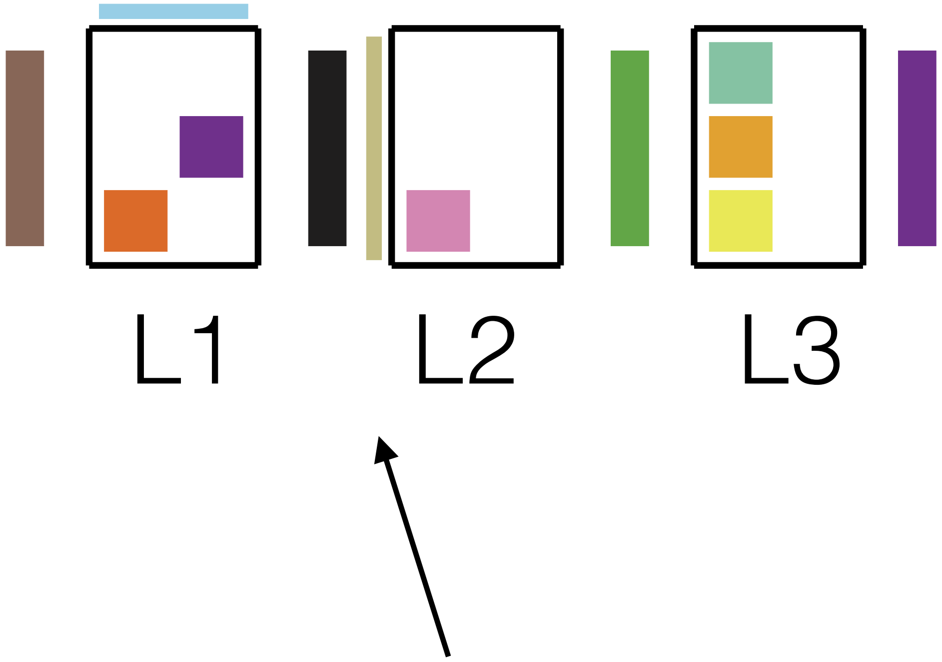
What do these events look like?

e.g. Run 1013, File 363, Event 751



Very large pulses from through-going muon in bars

Smaller pulses in slabs as less scintillator



channel map (L1 closest to IP, view from IP)

But what would mCP look like? Need to calibrate!

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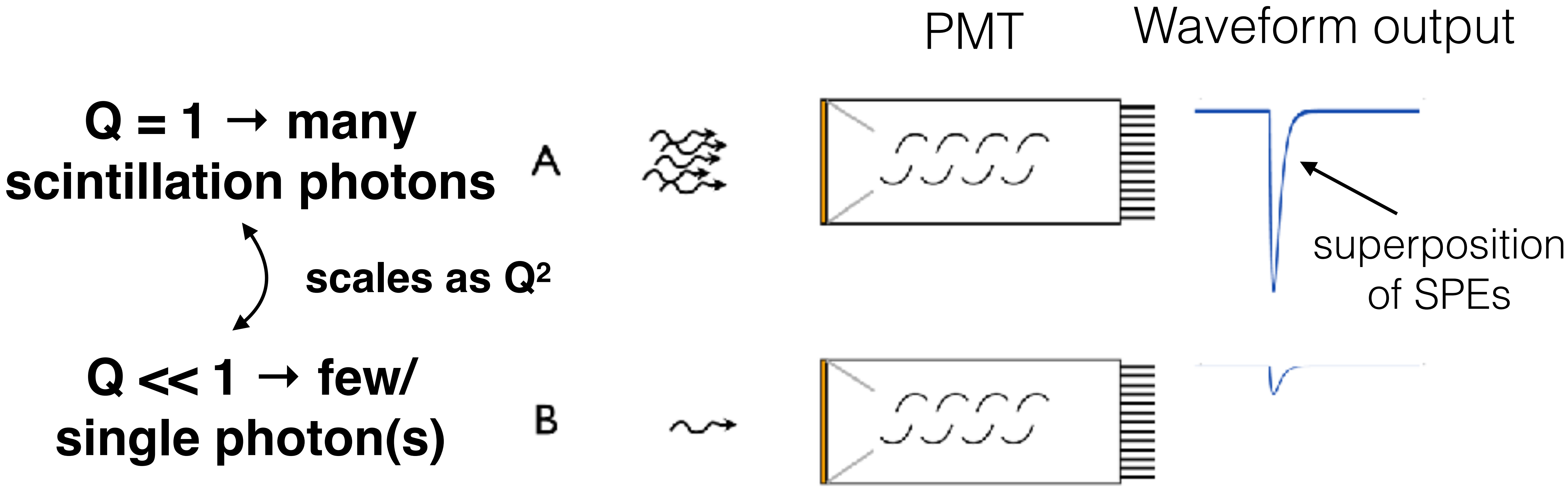
What will our signal look like?



PMT

Waveform output

Q = 1 → many scintillation photons

scales as Q^2

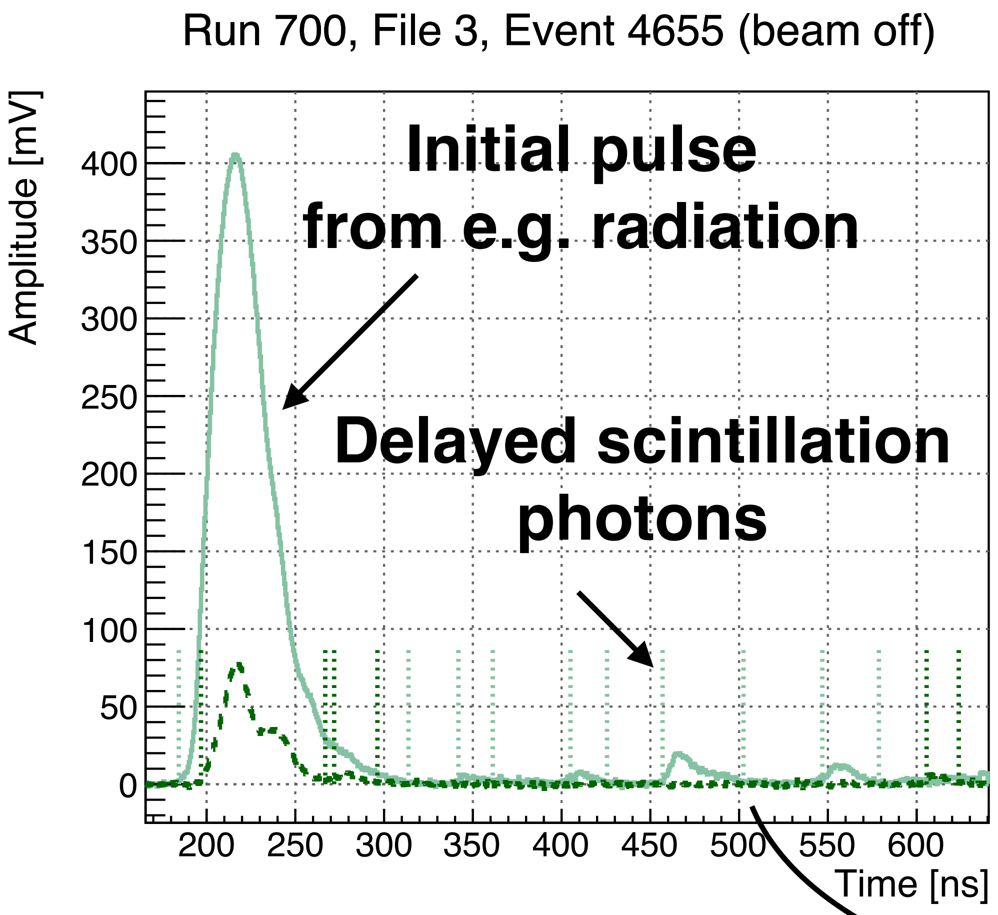
Q << 1 → few/ single photon(s)

superposition of SPEs

- Need to know number of photons (N_{PE}) produced for a given Q
- First measure area of single photon events (SPE)
- Then use linearity: $N_{PE}(Q=1e)$ = pulse area (cosmic)/pulse area SPE
- **Vital calibration** for detector simulation

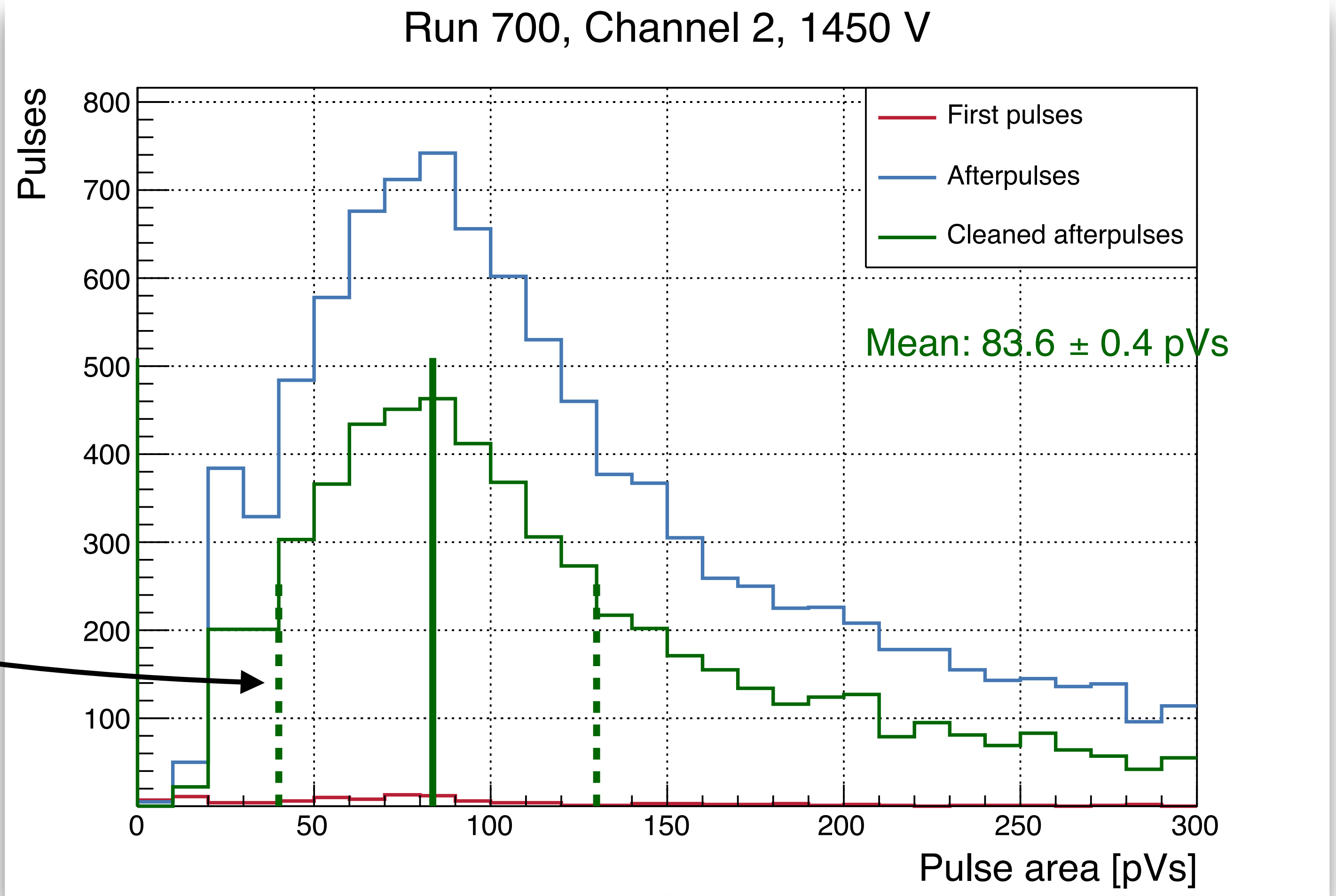
SPE area calibration in-situ

SPE measurement validated using LED on test bench (see backup)


Run 700, File 3, Event 4655 (beam off)

Initial pulse from e.g. radiation

Delayed scintillation photons


Run 700, Channel 2, 1450 V

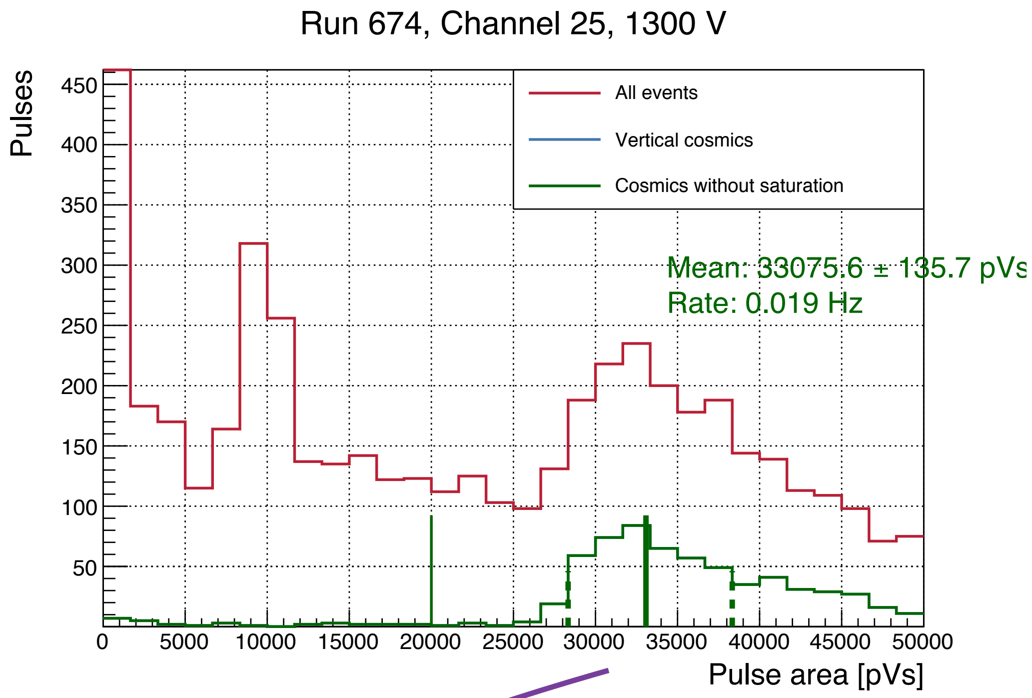
Build up pulse area distribution from ‘cleaned afterpulses’ (no pulse in preceding 20ns)

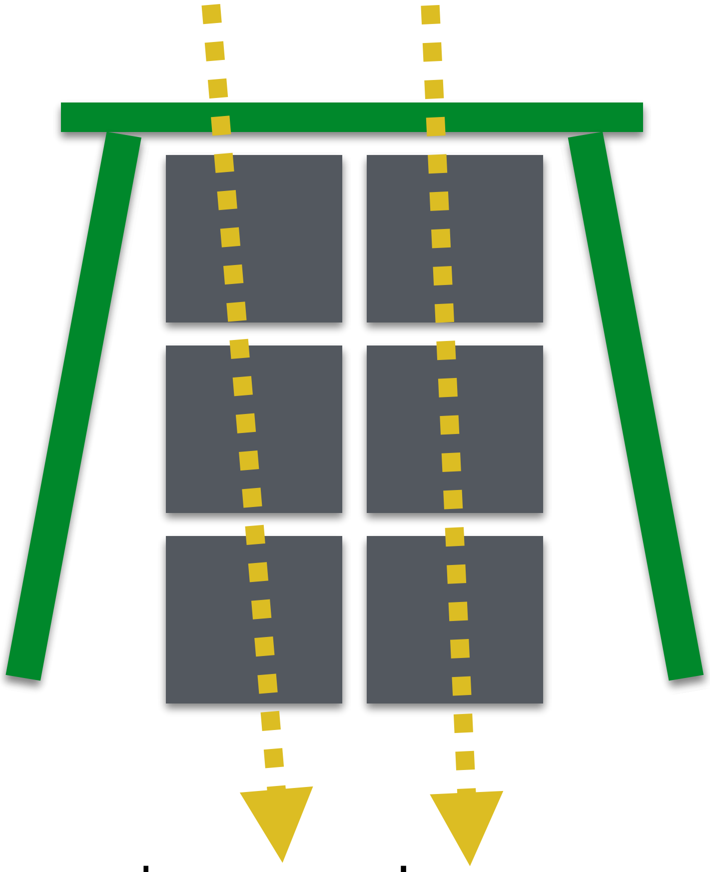
e.g. R878 PMT

Mean within half-width-max gives SPE pulse area

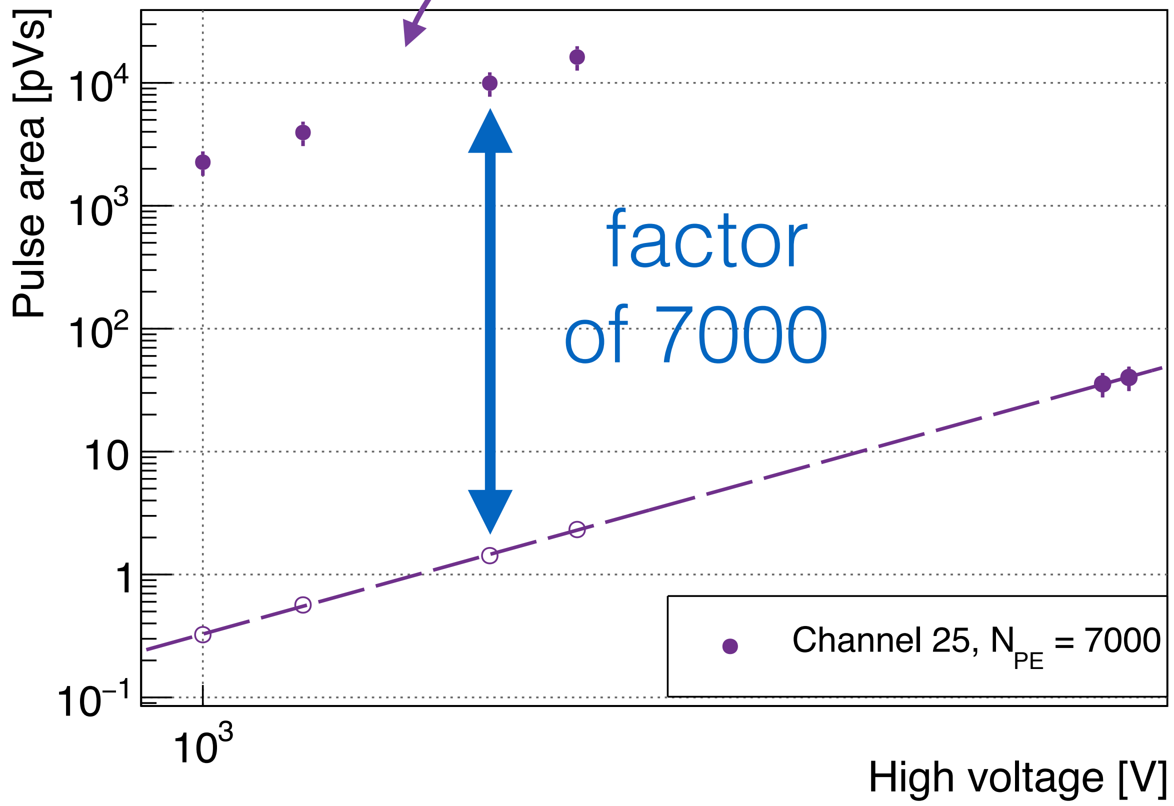
Cosmic light yield

- Cosmic pulse area from ‘down-going’ cosmics (avoid saturation regime)
- Area of cosmic and SPE vary identically with HV (power law) → NPE given by ratio of straight line fit to log-log plot

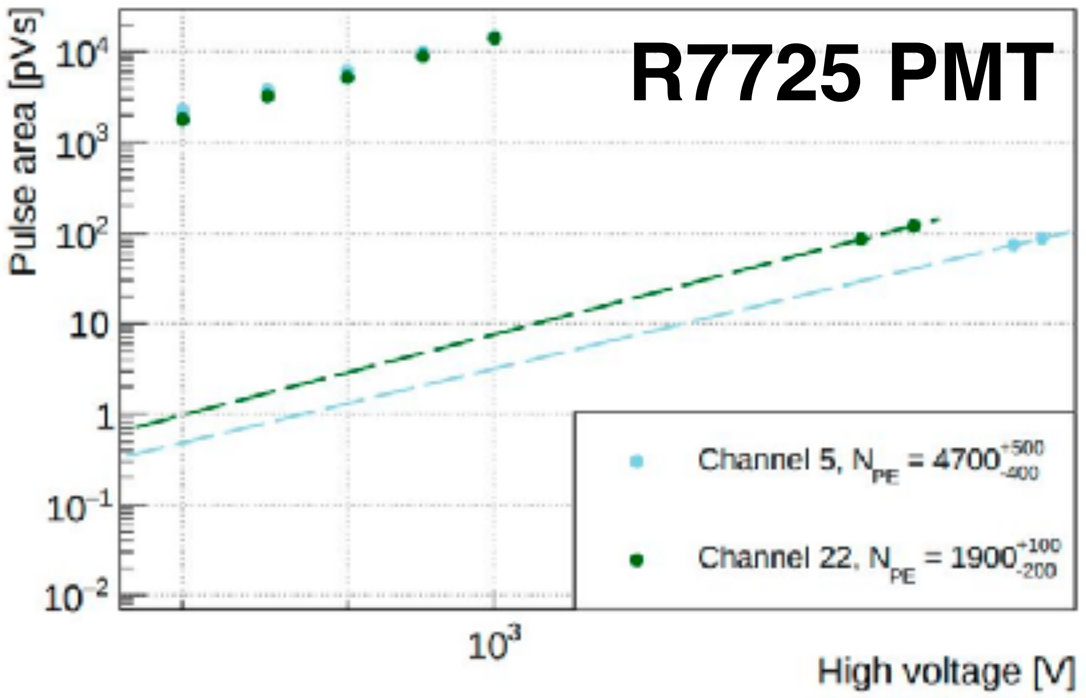


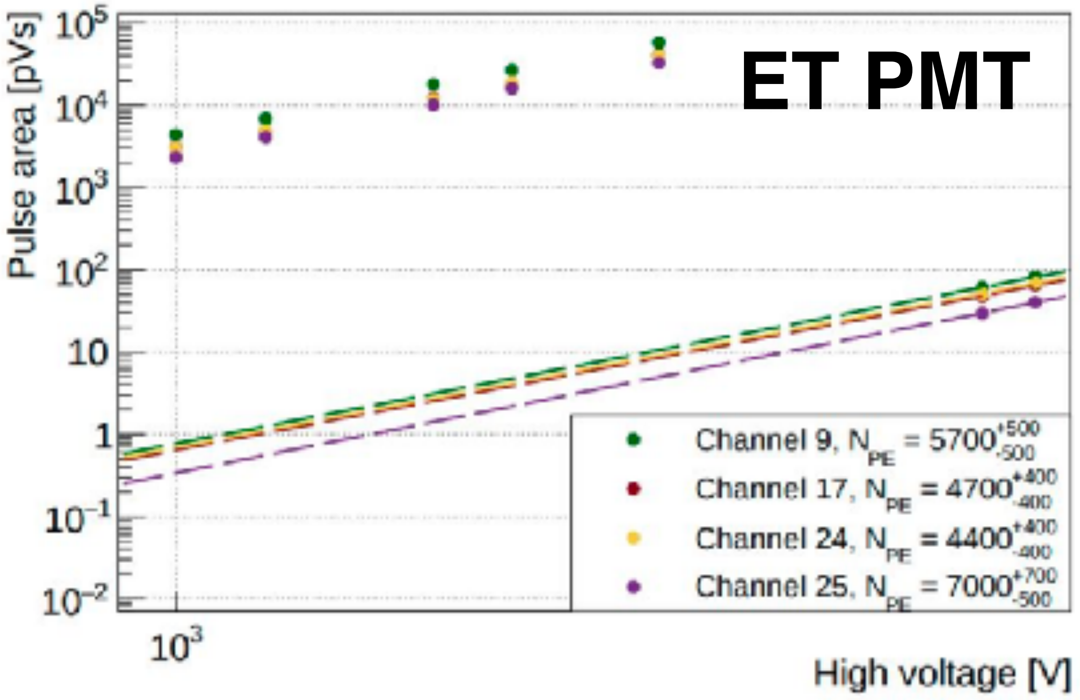


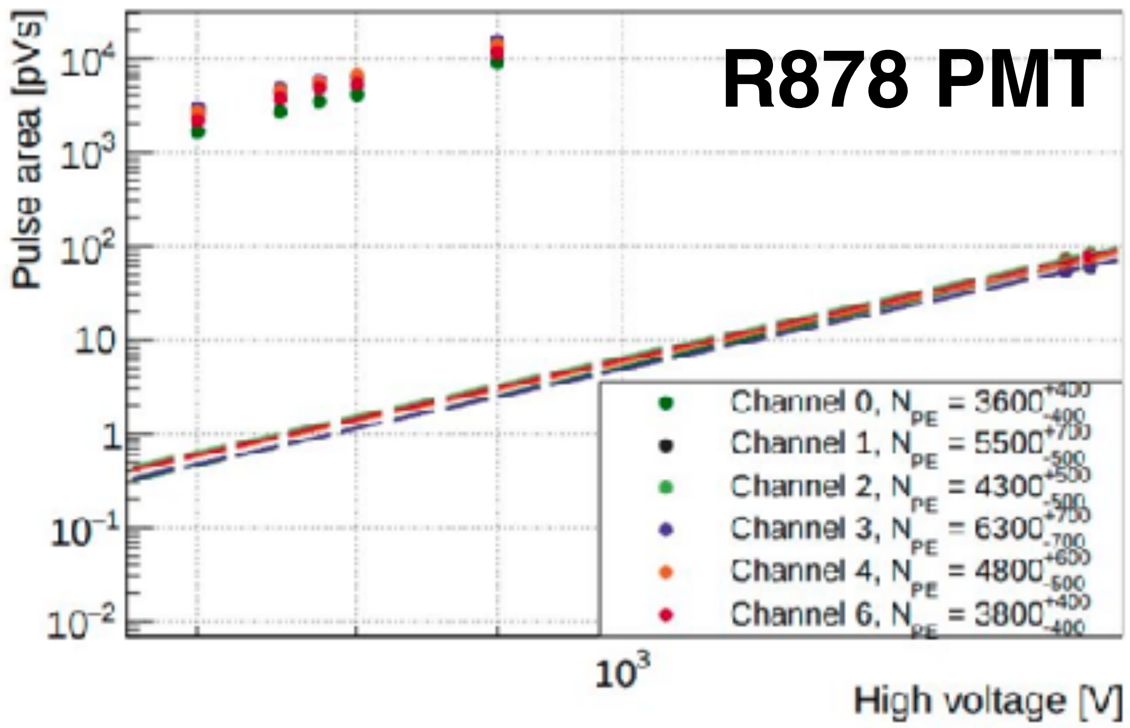
Use downgoing muons to avoid saturation



Cosmic light yield







N_{PE} ~O(5000) for all bars

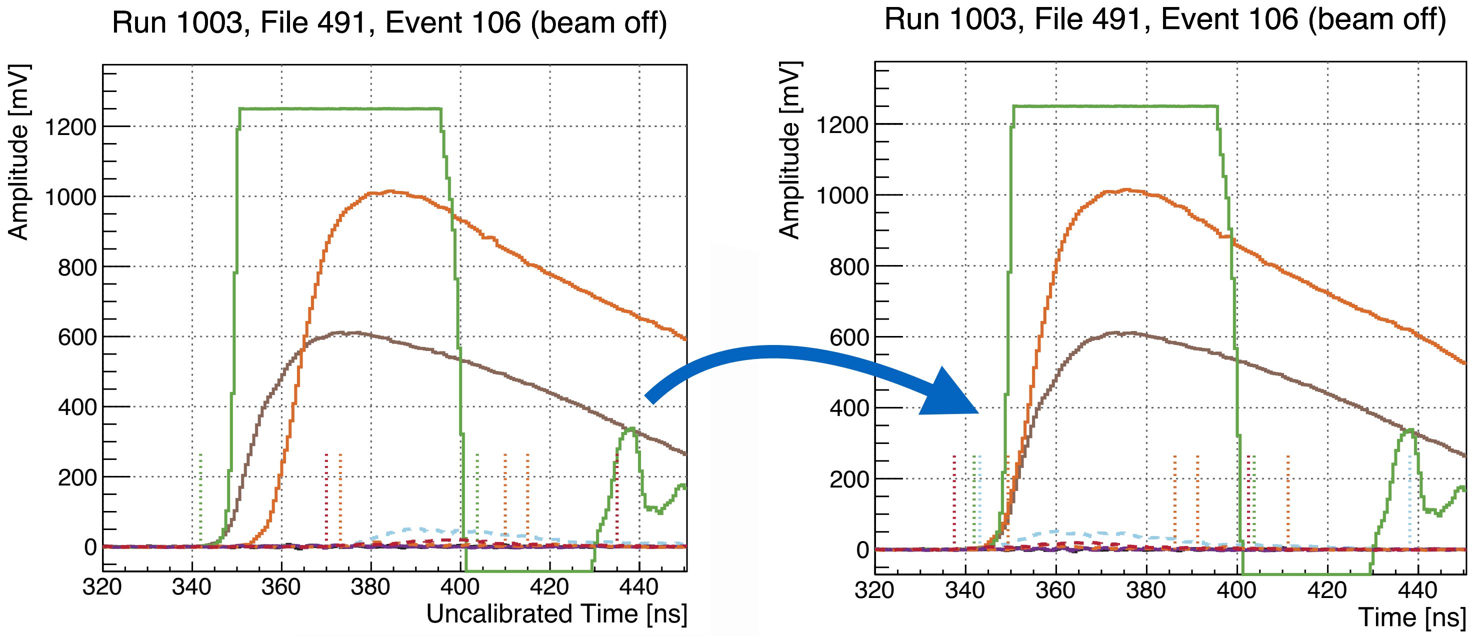
Scale for low charge (but through-going)

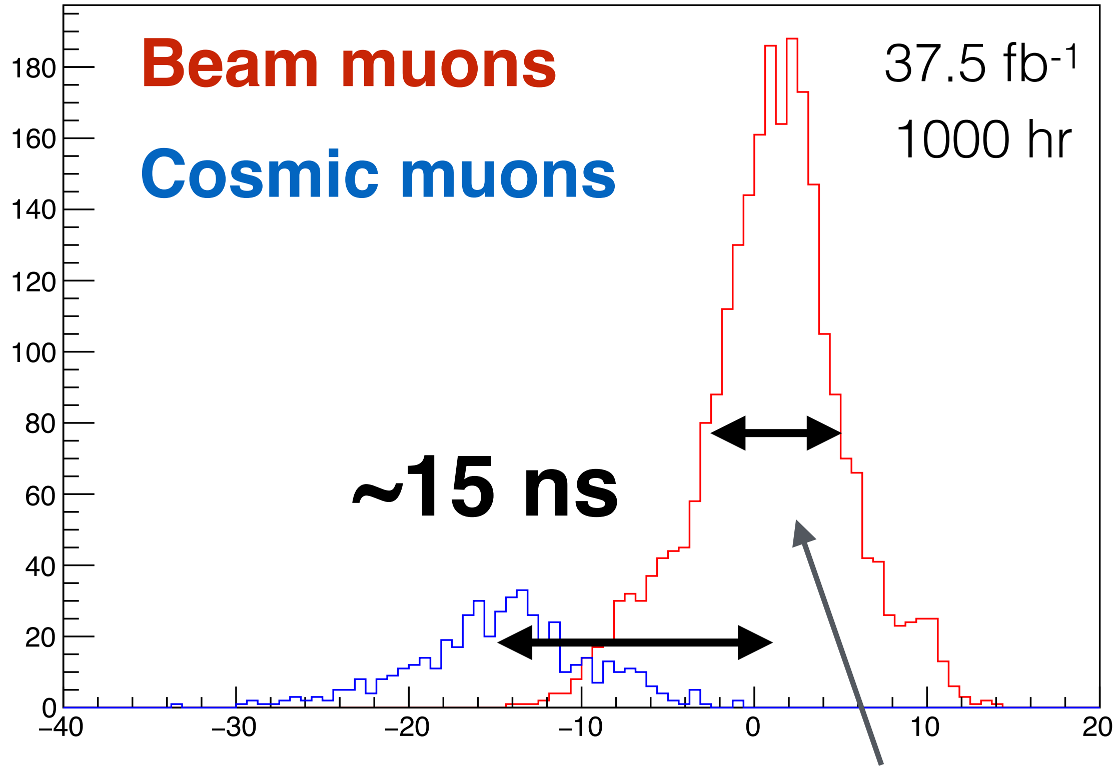
$$N_{PE} \propto L_0 \times Q^2$$

Q = 0.01: ~8 photons
Q = 0.003: ~1 photon

Through-going particle timing

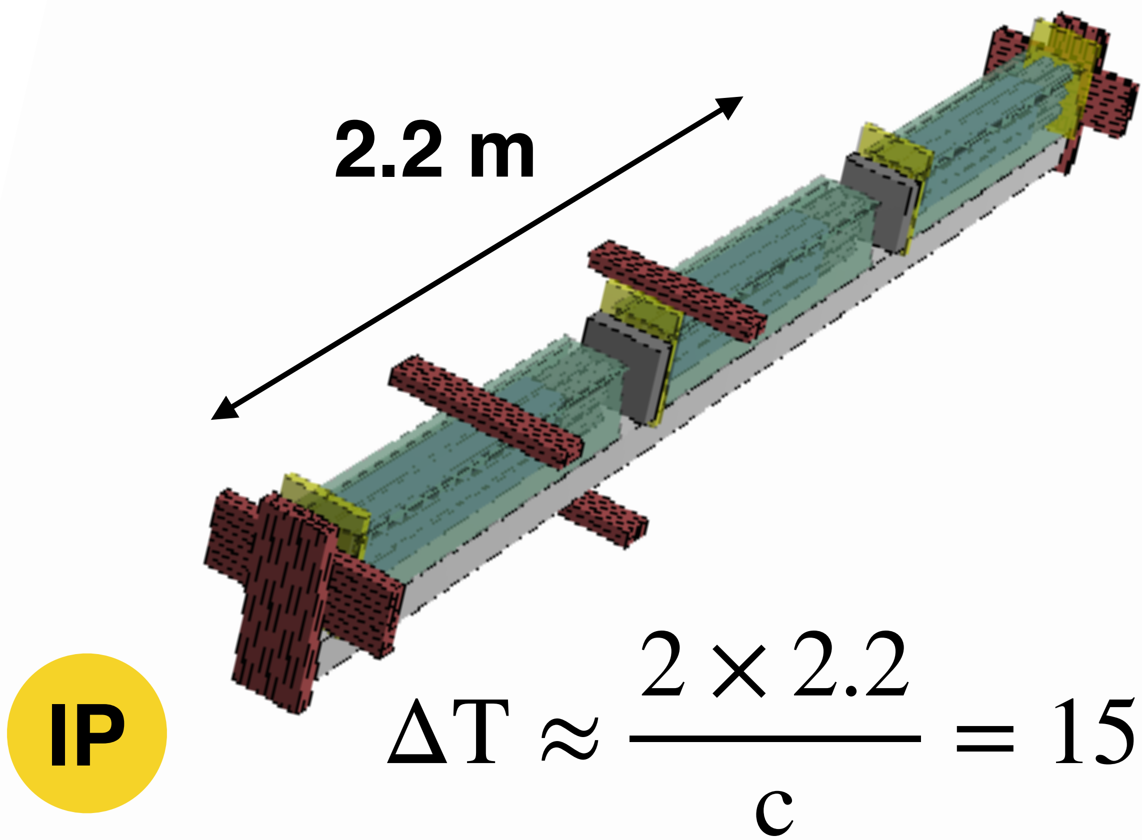
- Reject backgrounds using **small time window** between hits in each layer
- Cable length, PMT rise time and geometric differences must be calibrated
- Resolution ~4 ns → easily sufficient to define 15 ns time window for signal region!





~15 ns

resolution ~4ns



$$\Delta T \approx \frac{2 \times 2.2}{c} = 15\text{ns}$$

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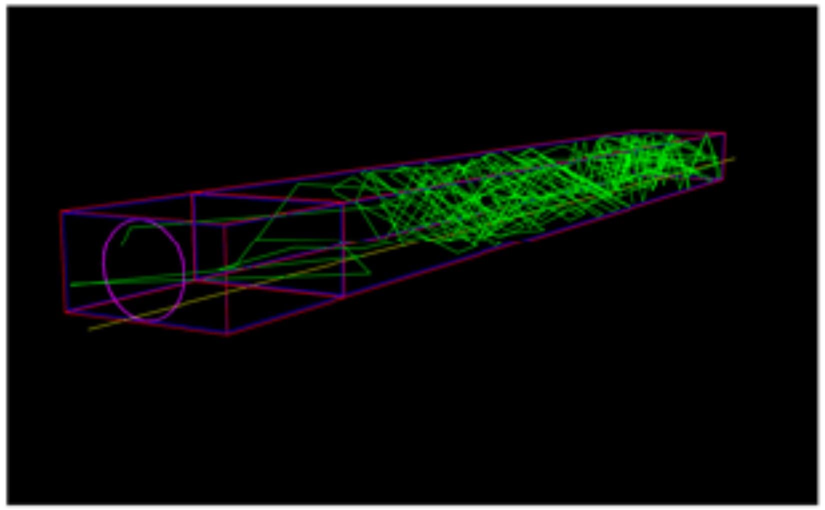
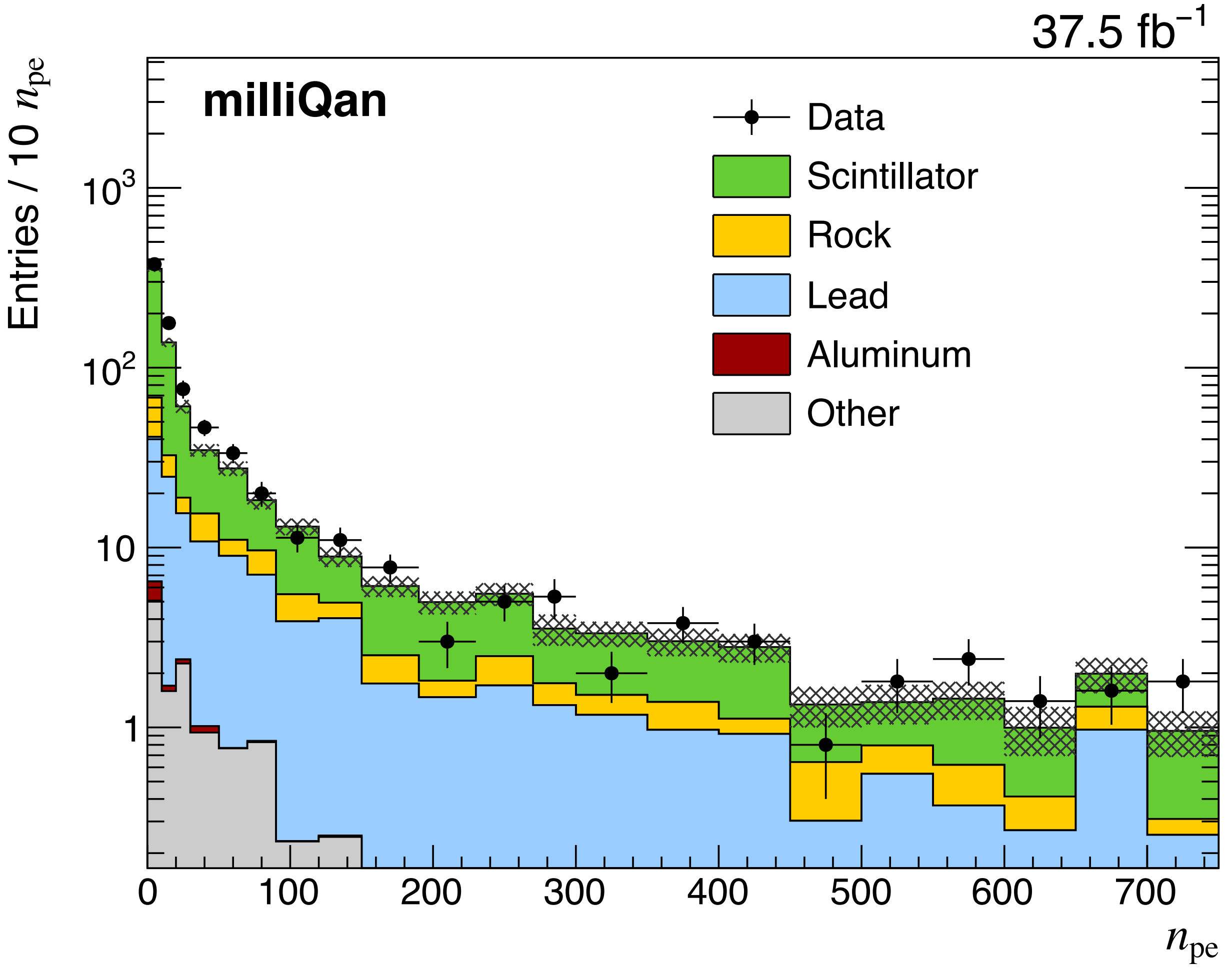
Detector simulation



- Full GEANT4 simulation of milliQan demonstrator for signals and cosmic/beam muon backgrounds
- Models reflectivity, light attenuation length and shape of scintillator
- Calibrate the quantum efficiency of each PMT in simulation based on the **measured** cosmic muon N_{PE}
- Comparison of muon shower N_{PE} in data and simulation shows **good agreement** across a wide range of energy depositions
- Detector **calibrated** and simulation **validated** → search for millicharged particles!



Number of PE in bars due to muon shower products

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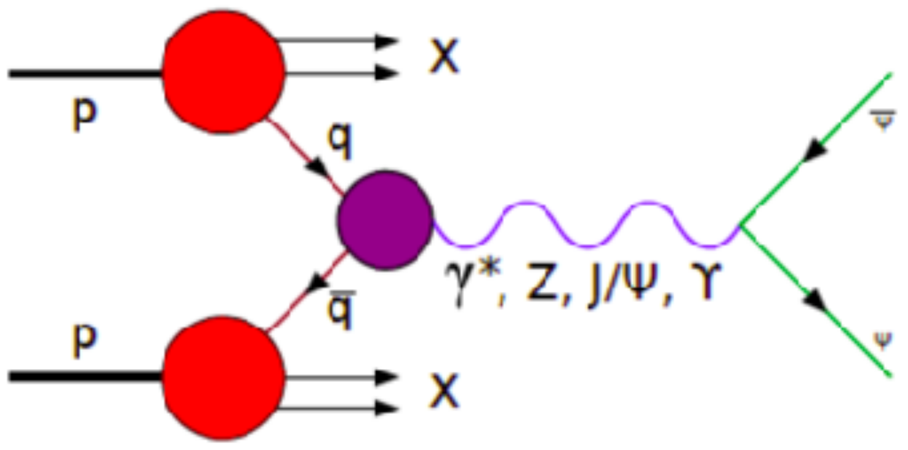
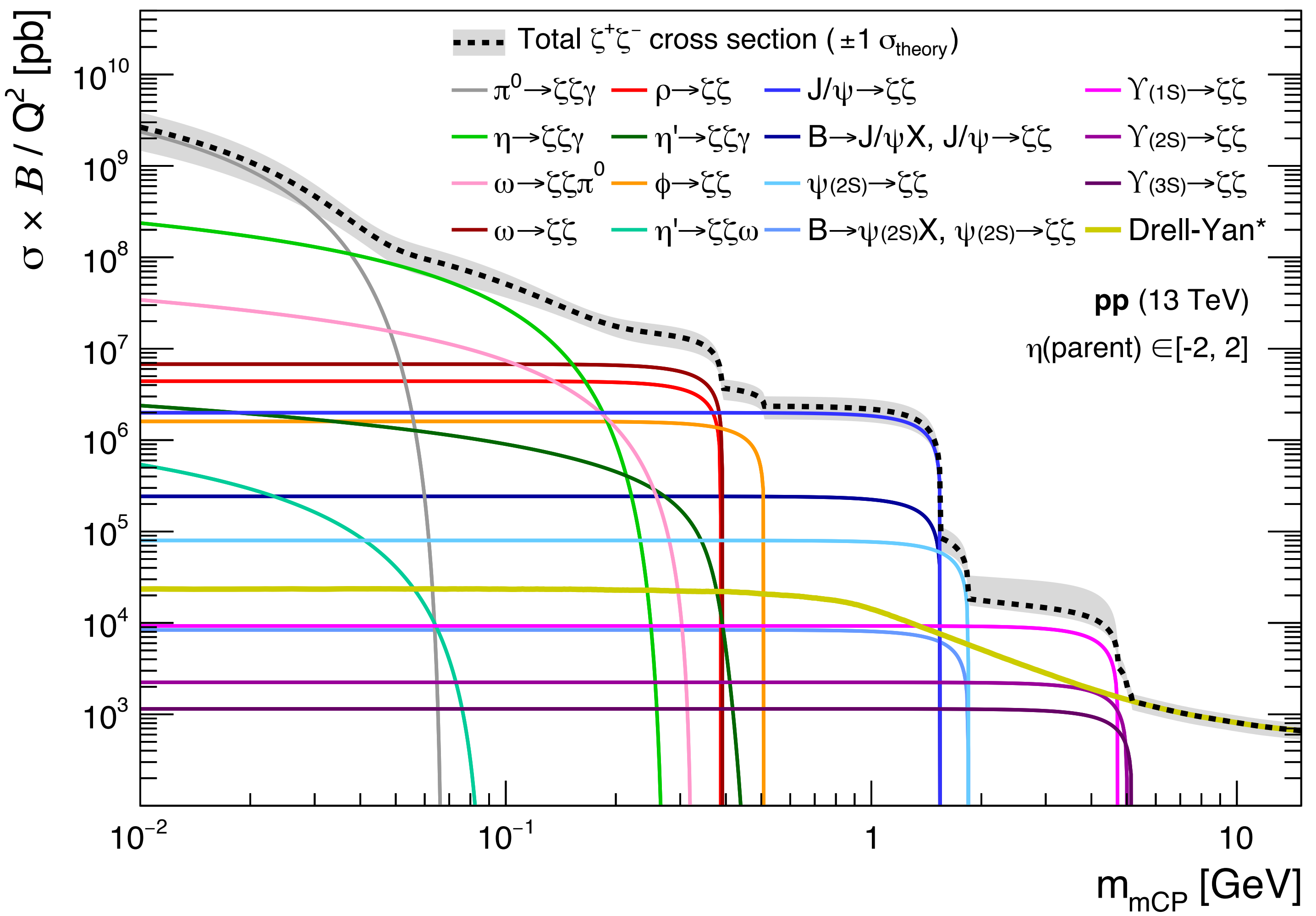
Signal simulation

- Wide range of mCP production mechanisms considered!
    - Drell-Yan, vector mesons, Dalitz decays, …

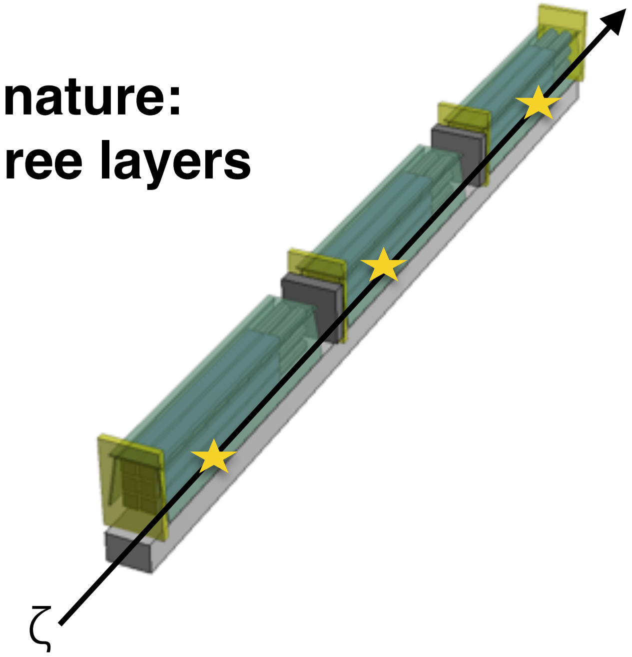
- Propagate to detector considering **multiple scattering** and **CMS magnetic field**

- Passed to GEANT4 simulation 2 m before detector face





Search signature: pulse in all three layers

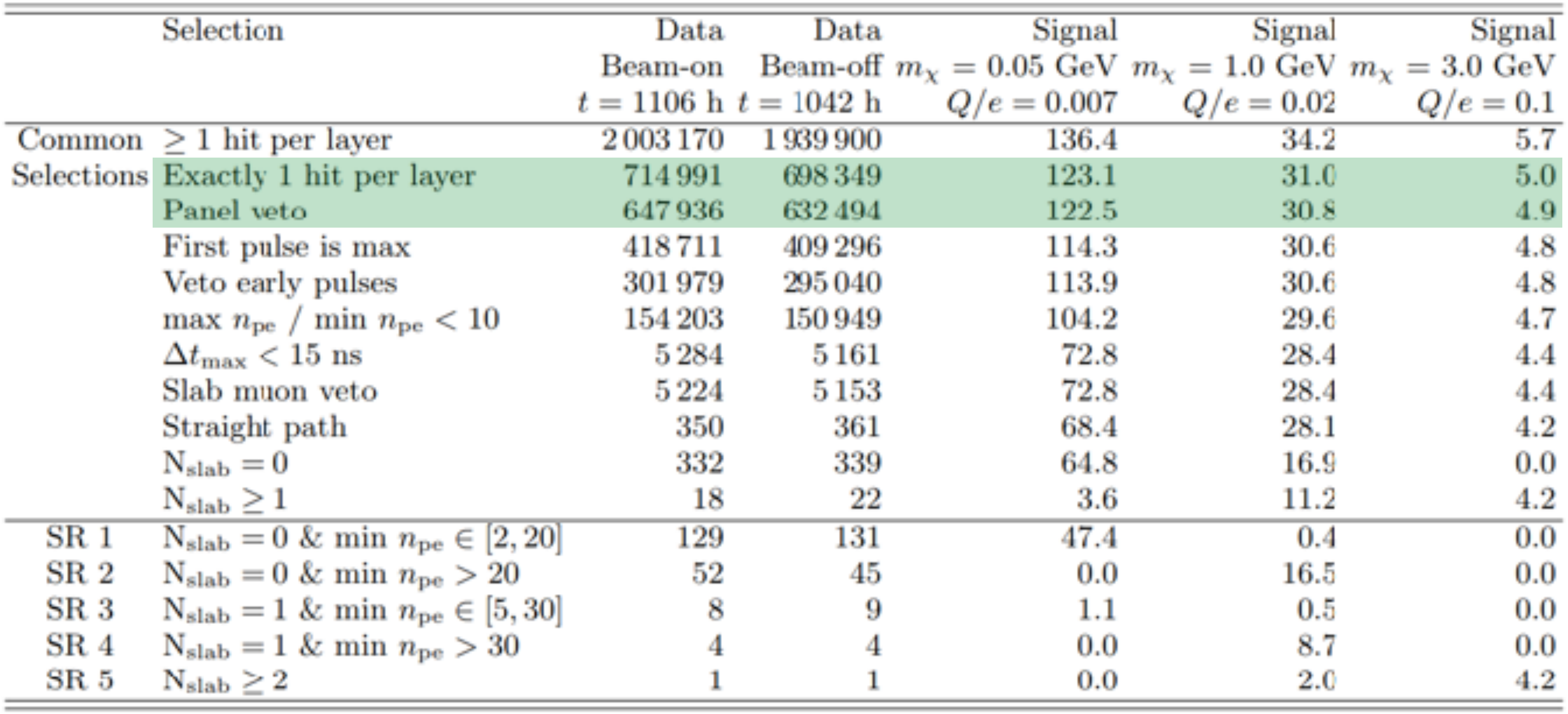


Background Sources

- Many background processes can cause a pulse in each layer including:
    - **PMT dark rate**: overlap of dark counts from three PMTs (or one PMT and two correlated background hits)
    - **Cosmic and beam muon shower secondaries** (especially electrons and gammas) can cause a pulse in each layer of the demonstrator
    - **Radiation** from the cavern, bars, or surrounding material (mostly Pb shielded)
    - **Afterpulses**: small, delayed pulses in PMTs caused by ionisation of residual gases following an initial detection
- Apply a range of selections to reject these backgrounds!

Signal selection and categorisation

Selections: event must have a hit per layer with **exactly 3 bar hits (no panel hits),**

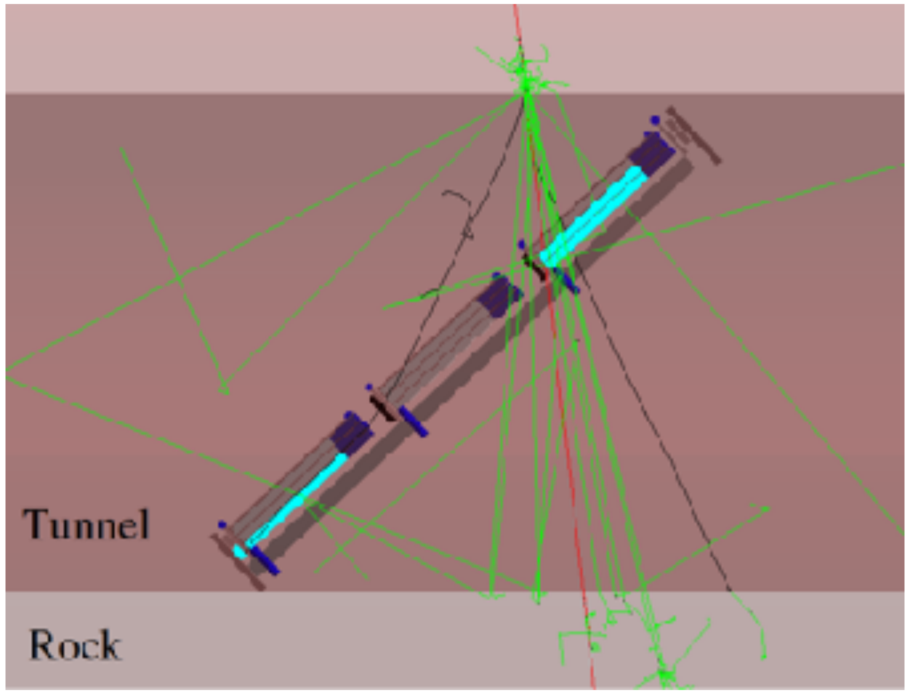


	Selection	Data	Data	Signal	Signal	Signal
		Beam-on	Beam-off	$m_\chi = 0.05$ GeV	$m_\chi = 1.0$ GeV	$m_\chi = 3.0$ GeV
		$t = 1106$ h	$t = 1042$ h	$Q/e = 0.007$	$Q/e = 0.02$	$Q/e = 0.1$
Common Selections	≥ 1 hit per layer	2 003 170	1 939 900	136.4	34.2	5.7
	Exactly 1 hit per layer	714 991	698 349	123.1	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
	$\Delta t_{\max} < 15$ 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

Veto backgrounds from cosmic muon shower secondaries

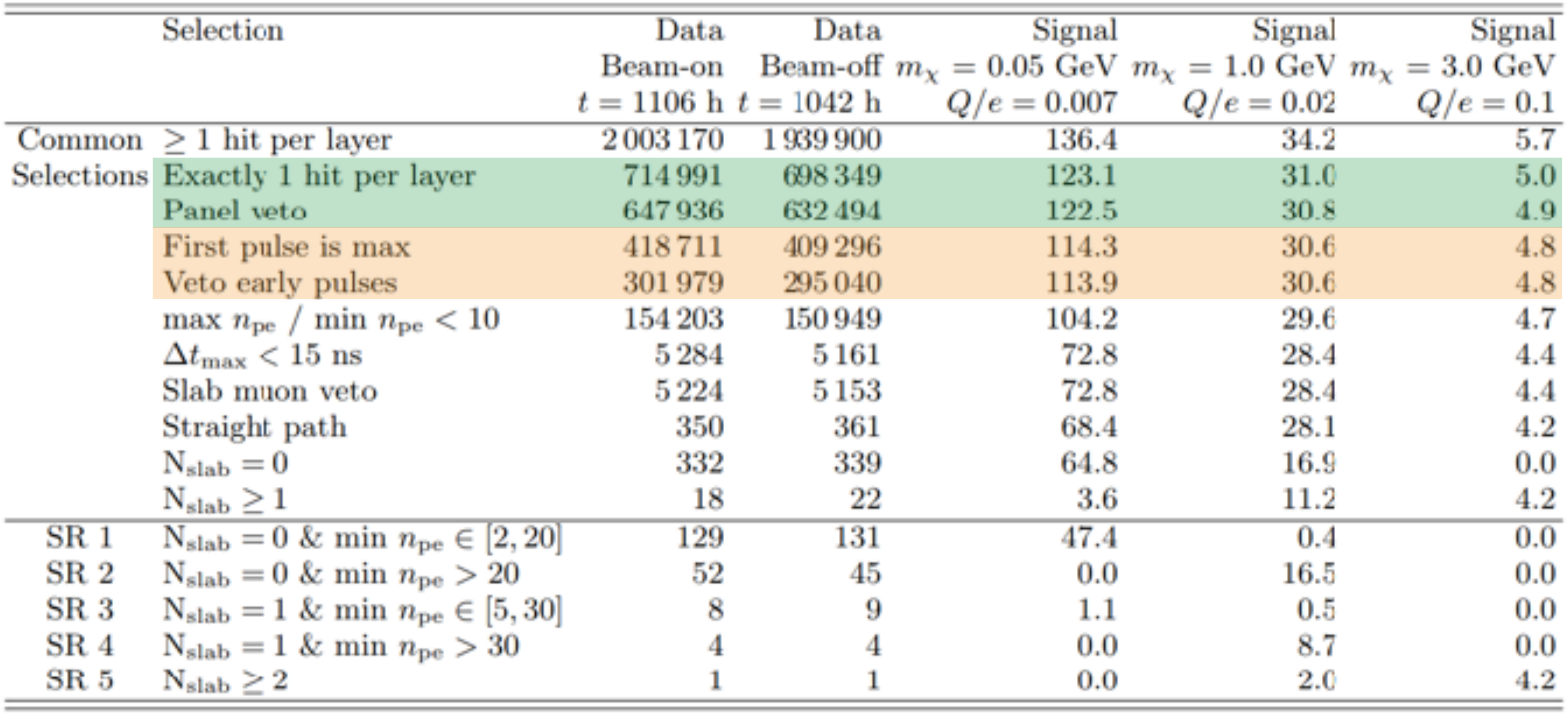
e.g. simulated event

Muon and shower secondaries: gammas, electrons, photons



Signal selection and categorisation

Selections: event must have a hit per layer with **exactly 3 bar hits (no panel hits), well behaved signal amplitudes,**



	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 $Q/e = 0.1$
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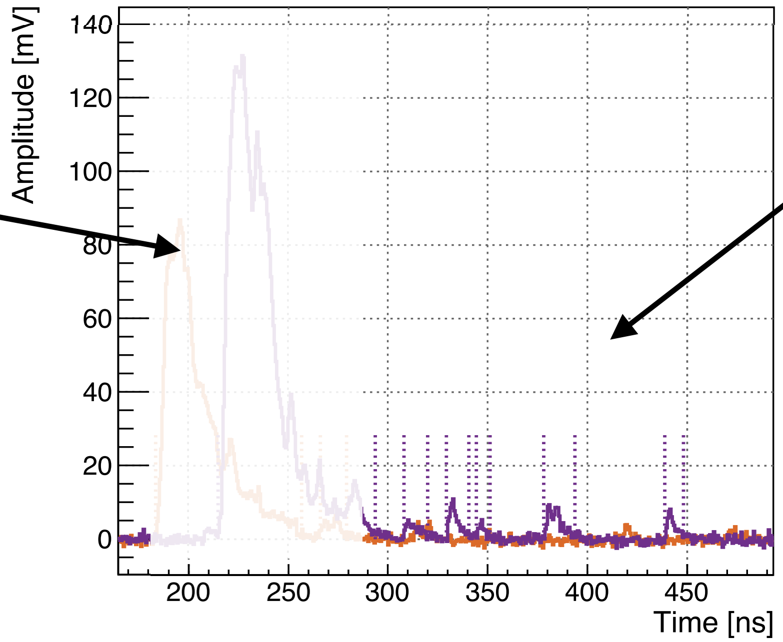
	First pulse is max	418 711	409 296	114.3	30.6	4.8
	Veto early pulses	301 979	295 040	113.9	30.6	4.8
	max n_{pe} / min $n_{\mathrm{pe}} < 10$	154 203	150 949	104.2	29.6	4.7
	$\Delta t_{\mathrm{max}} < 15$ ns	5 284	5 161	72.8	28.4	4.4
	Slab muon veto	5 224	5 153	72.8	28.4	4.4
	Straight path	350	361	68.4	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

Veto backgrounds from "junk" such as afterpulsing

Initial pulse missed



Afterpulses overlap

NB: trigger dead time of ~100μs makes this very unlikely!

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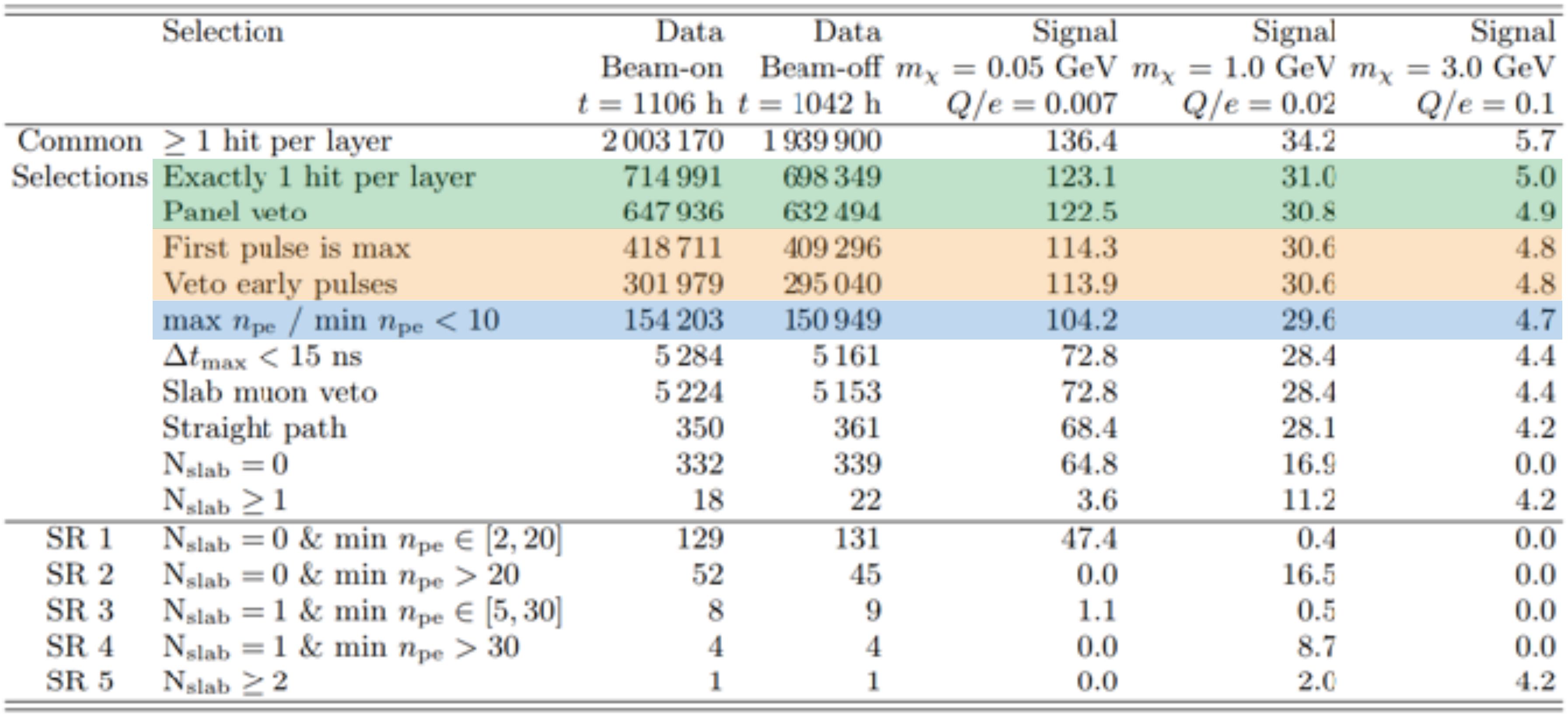
Signal selection and categorisation

Selections: event must have a hit per layer with **exactly 3 bar hits (no panel hits)**, **well behaved signal amplitudes**, **similar energy depositions in each layer**,



	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 Selections	≥ 1 hit per layer	2 003 170	1 939 900	136.4	34.2	5.7
	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
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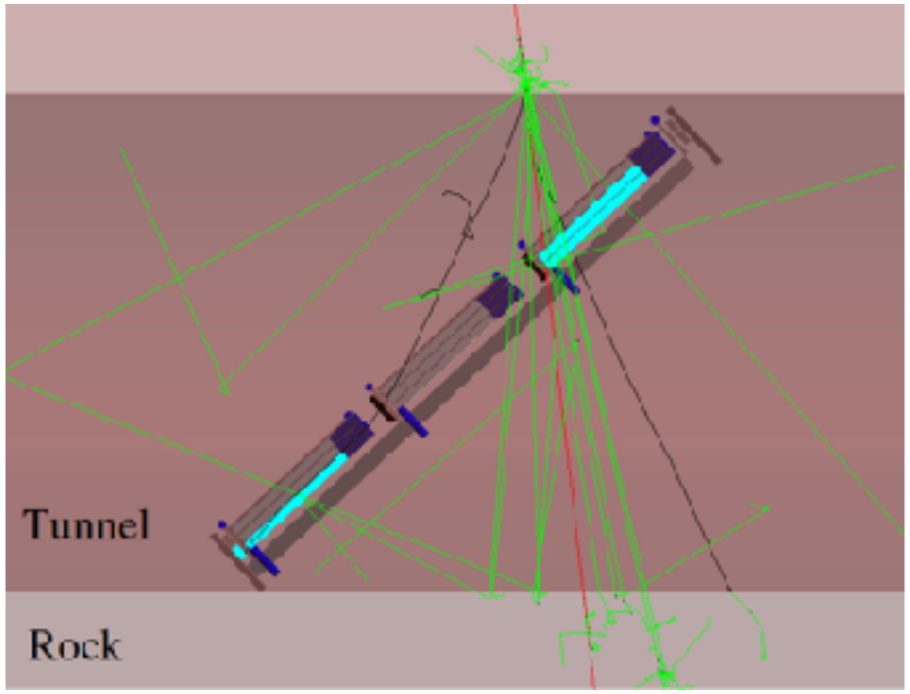
SR 5	$\text{N}_{\text{slab}} \geq 2$	1	1	0.0	2.0	4.2

Veto backgrounds with deposit in each layer from different sources

e.g. simulated event

Muon and shower secondaries: gammas, electrons, photons



Signal selection and categorisation

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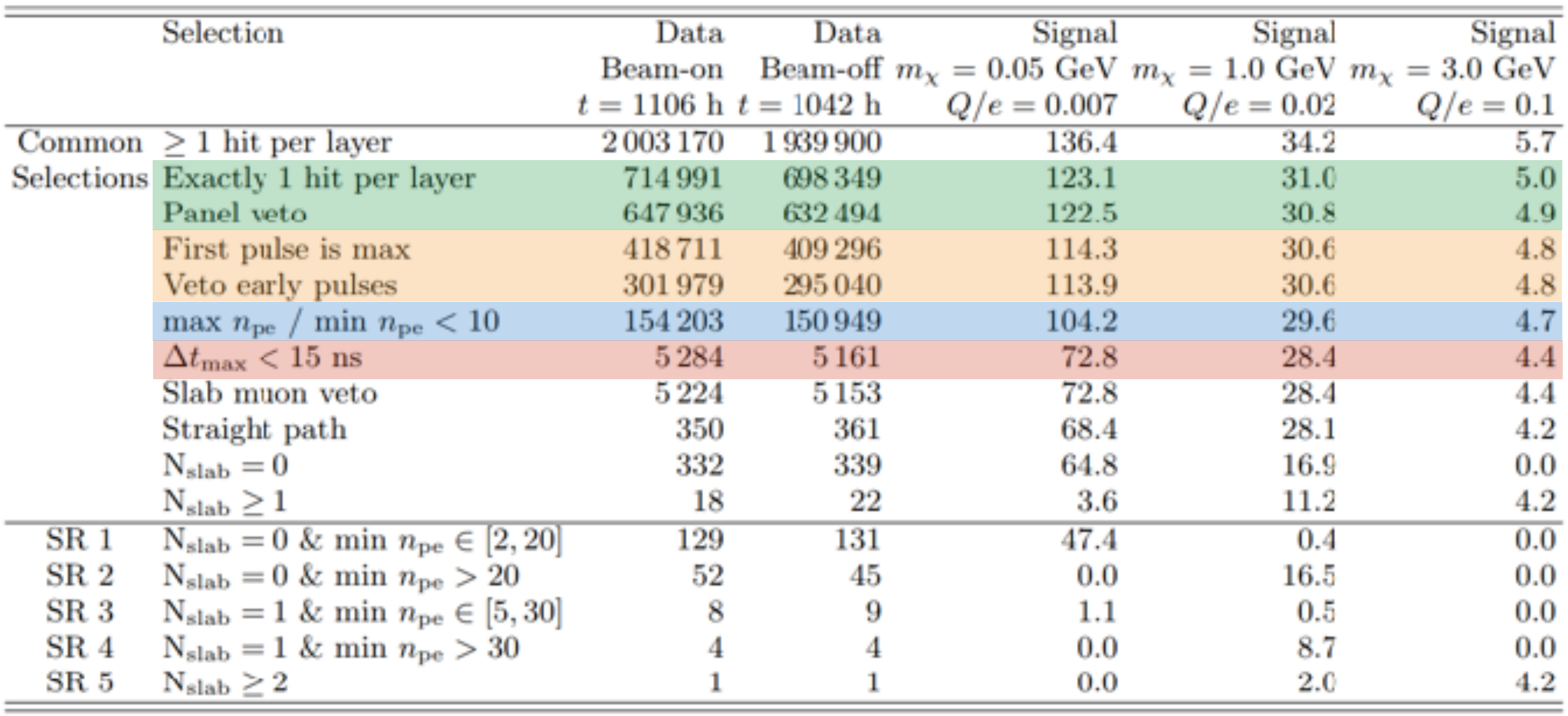

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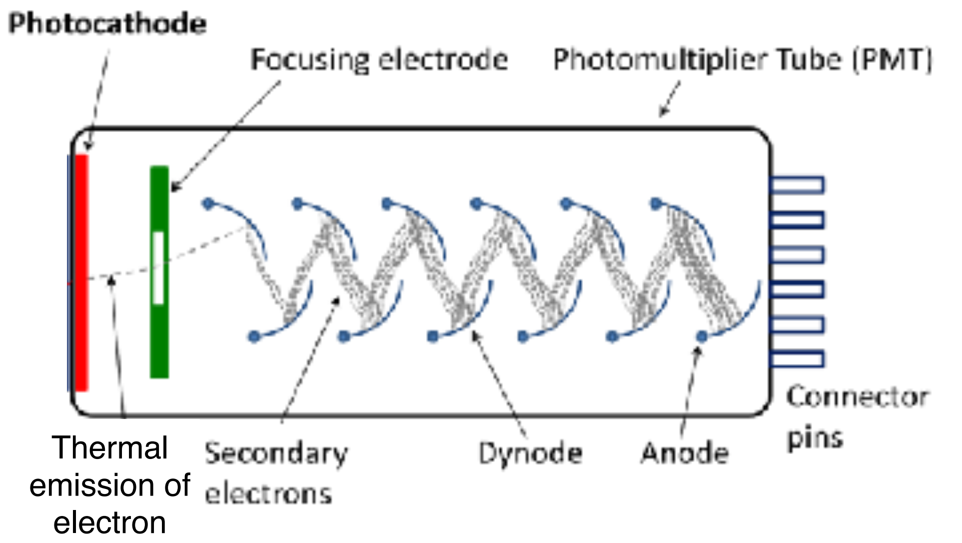
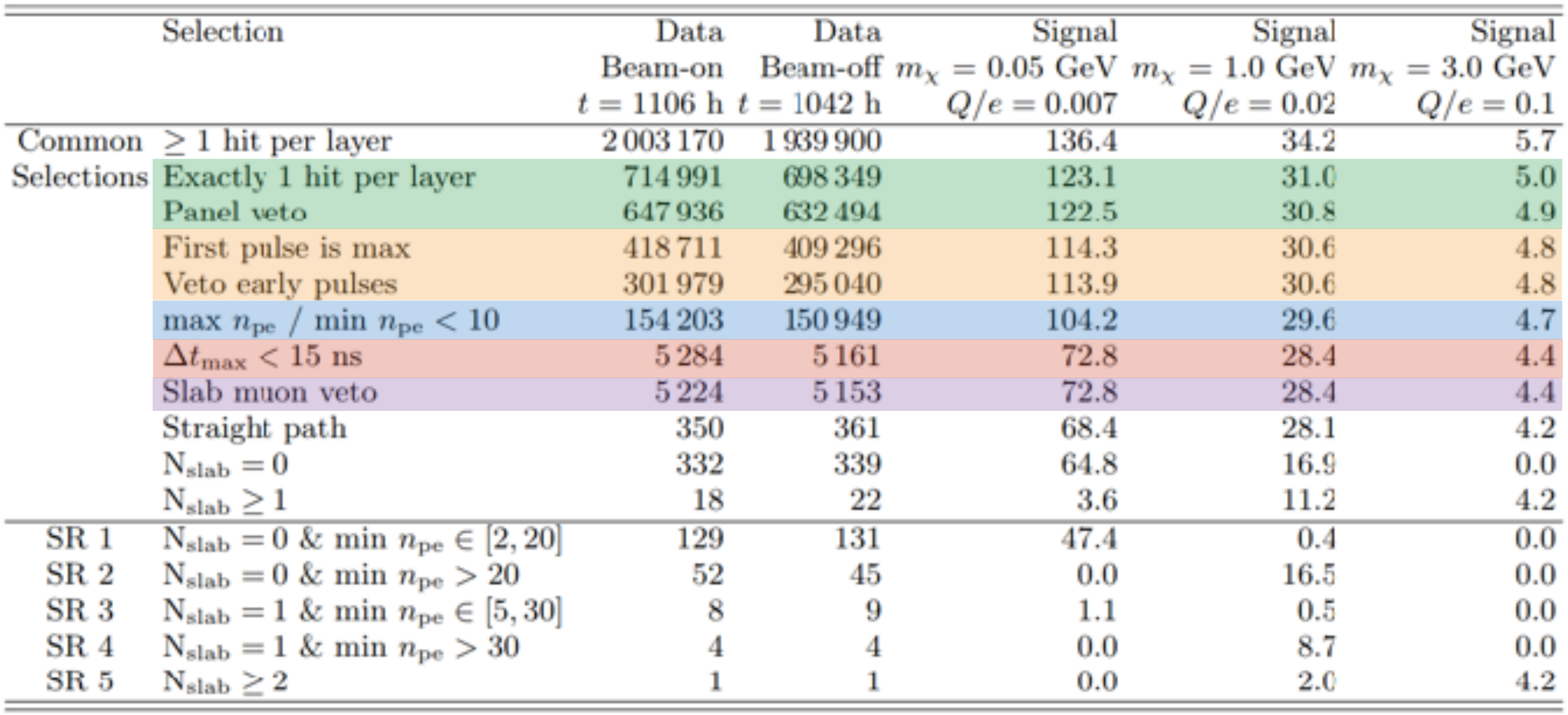
Veto backgrounds uncorrelated in timing such as overlapping dark rate pulses

PMT dark rate ~2kHz



Signal selection and categorisation

Selections: event must have a hit per layer with **exactly 3 bar hits (no panel hits), well behaved signal amplitudes, similar energy depositions in each layer, hits within a small time window, NPE not consistent with a muon,**



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SR 5	$\mathrm{N_{slab}} \geq 2$	1	1	0.0	2.0	4.2

Veto backgrounds from through going beam muons

beam muon

Veto with max NPE requirement in slabs

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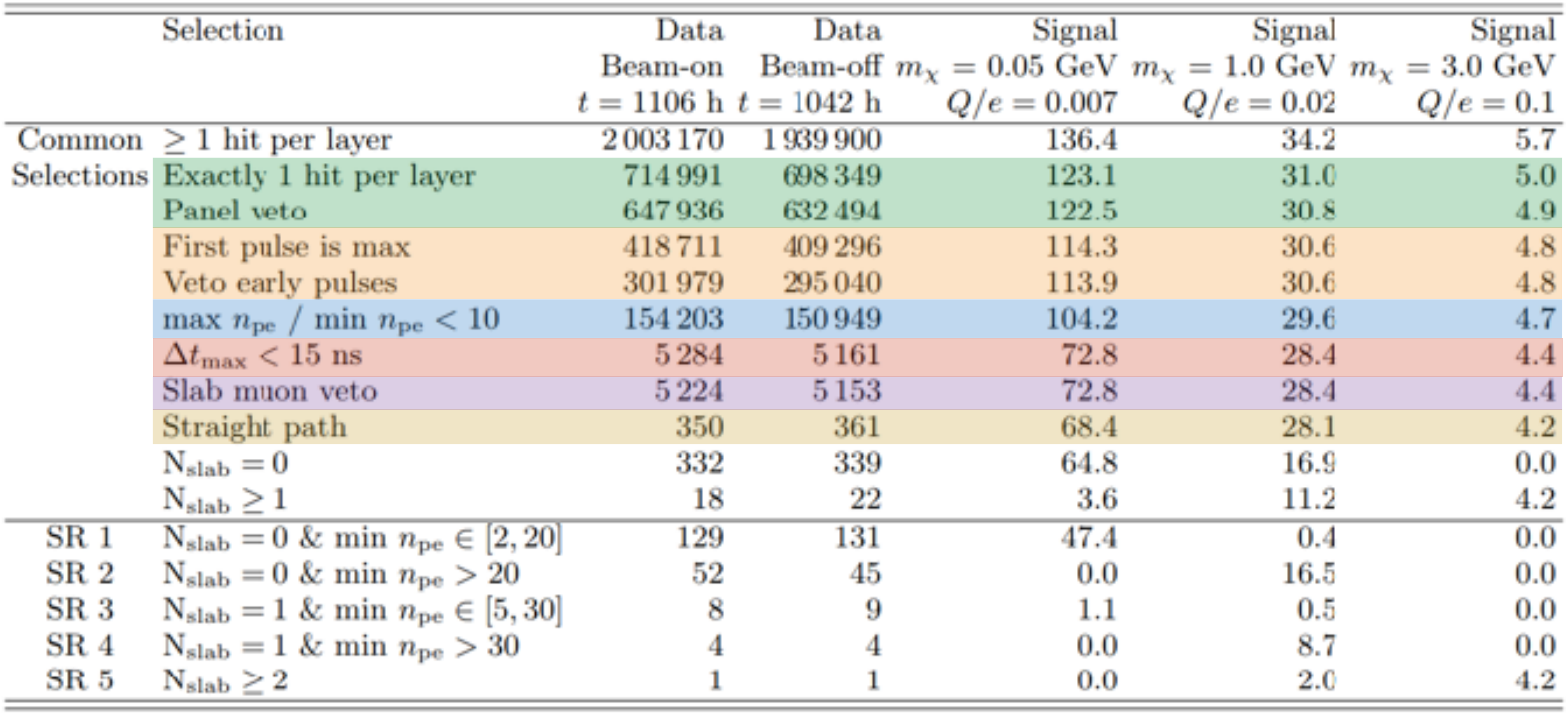
Signal selection and categorisation

Selections: event must have a hit per layer with **exactly 3 bar hits (no panel hits)**, **well behaved signal amplitudes**, **similar energy depositions in each layer**, **hits within a small time window**, **N_{PE} not consistent with a muon**, **straight line to the CMS IP**



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SR 5	$\text{N}_{\text{slab}} \geq 2$	1	1	0.0	2.0	4.2

Veto backgrounds uncorrelated in detector position

Selections reduce backgrounds by **5 orders of magnitude**

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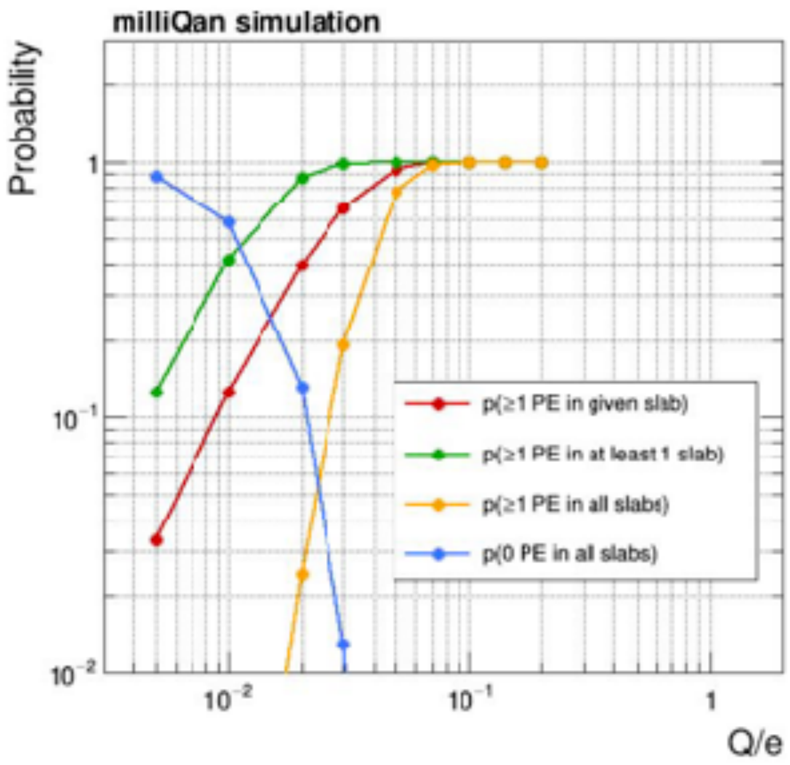
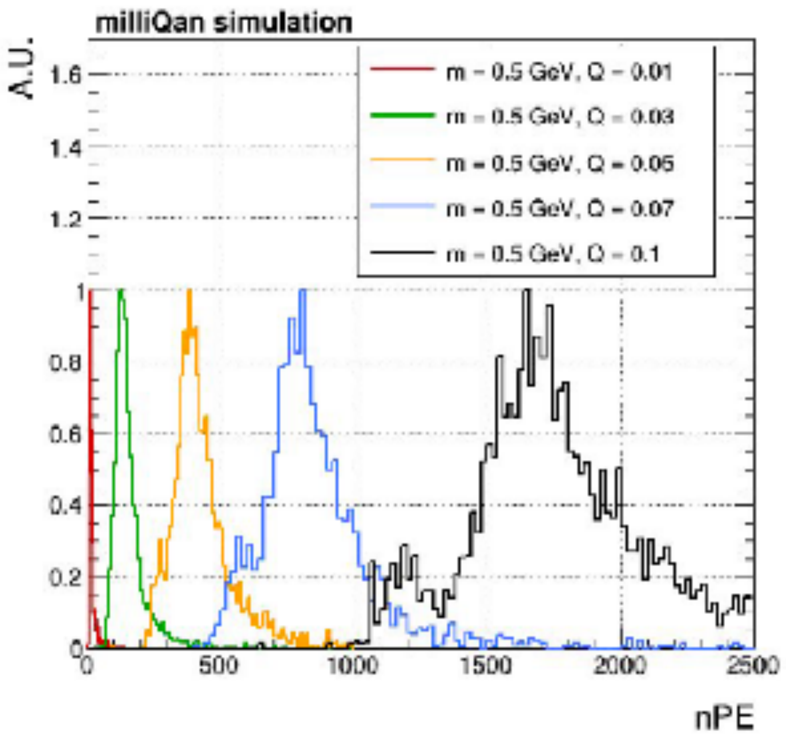
Categorisation

Categorise signal using NPE and slab deposits to optimise sensitivity for a wide range of charges

Requiring slab hits greatly reduces backgrounds for higher charges





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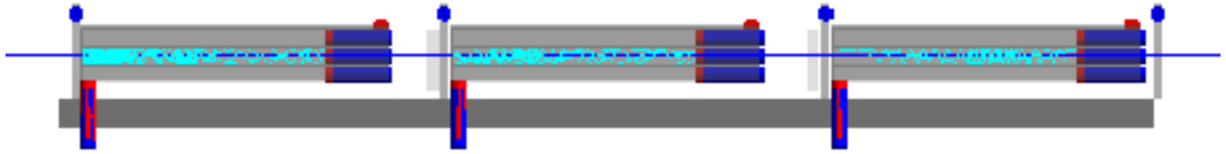
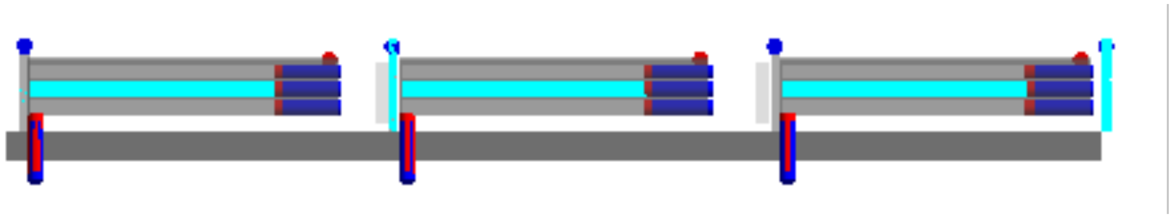
SR 5	$\mathrm{N_{slab}} \geq 2$	1	1	0.0	2.0	4.2

Q = 0.002e



Q = 0.01e



Sample through-going mCPs

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Background prediction

- Background predicted using ABCD method inverting **timing** and **pointing path** requirements in beam-on dataset
- Beam does not contribute to background (confirmed with simulation and data) → validate prediction using beam-off data

A	B
pointing path, $t < 15$ ns	**non-pointing path, $t < 15$ ns**
pointing path, $t > 15$ ns	**non-pointing path, $t > 15$ ns**
C	D

$$N_A = N_B . N_C / N_D$$

Use agreement between prediction and observation to derive systematic uncertainties on prediction

Background vs. Prediction (beam off)

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%

1042 hr beam off data collected

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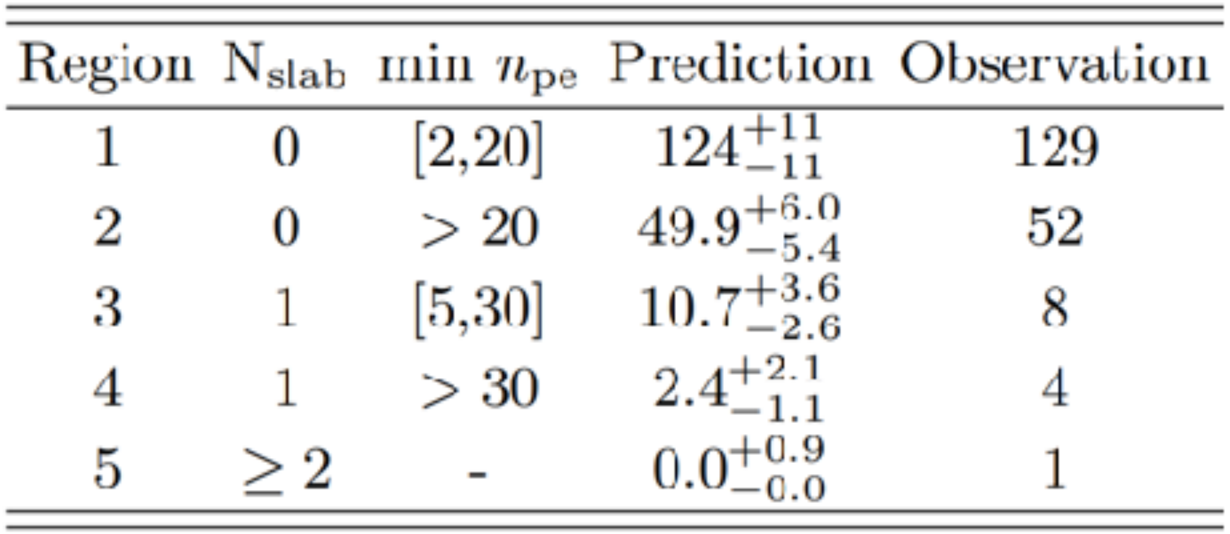
Background prediction

- Signal region: 37.5 fb^{-1} (1106 hr) of data for p-p collisions at 13 TeV collected during 2018 (86% of delivered lumi!)
- Predictions from ABCD with systematic uncertainties from beam-off validation

Signal region predictions and observations



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

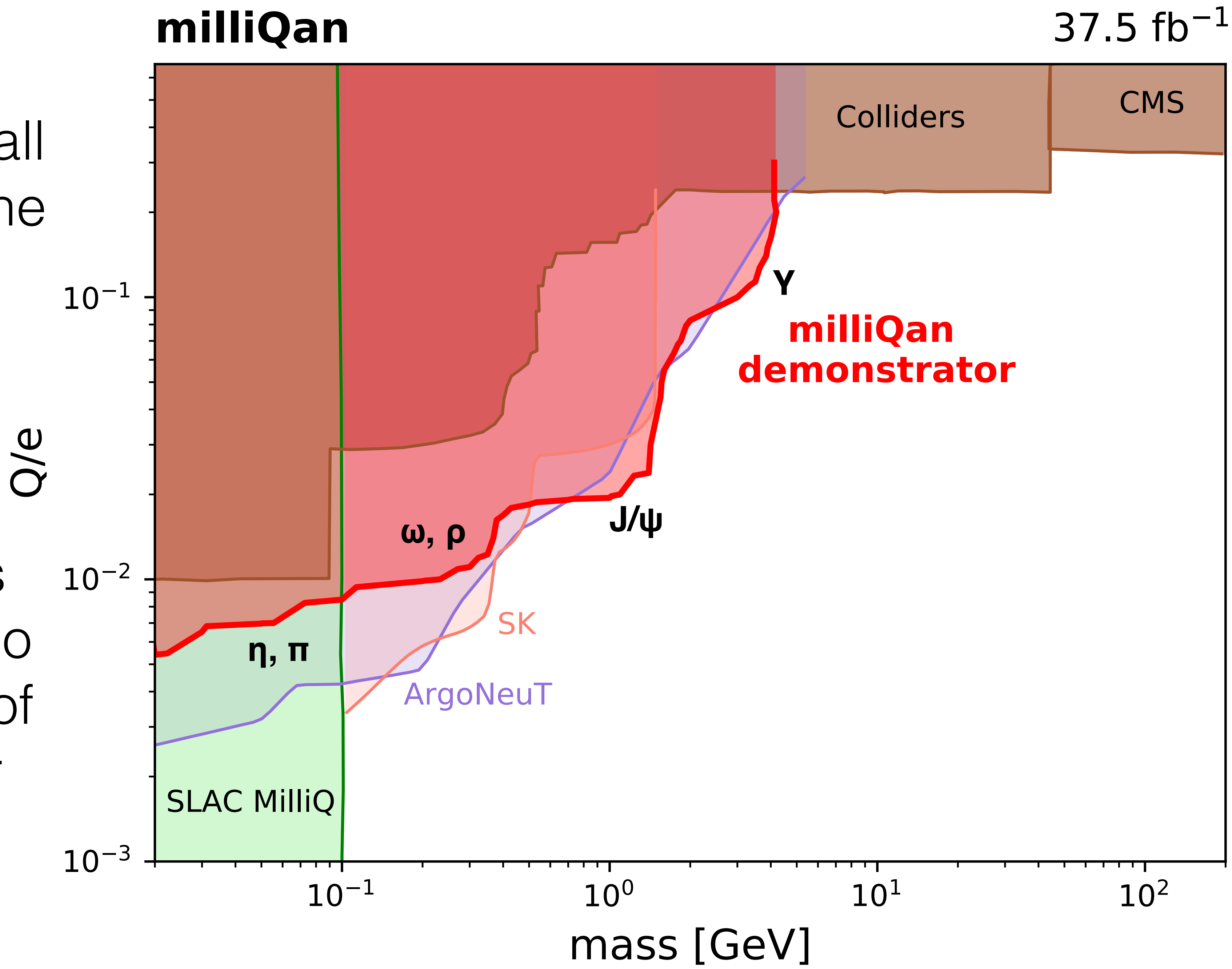
Good agreement with prediction in all SRs → derive exclusion limits on mass/charge

Search results

With only 37.5 fb^{-1} and a small fraction of the full detector, the milliQan demonstrator achieves competitive constraints on mCPs

The demonstrator provides new exclusion limits, but also quantitative understanding of backgrounds and detector performance

→ Use this to guide future detectors!



Published in PRD: PhysRevD.102.032002

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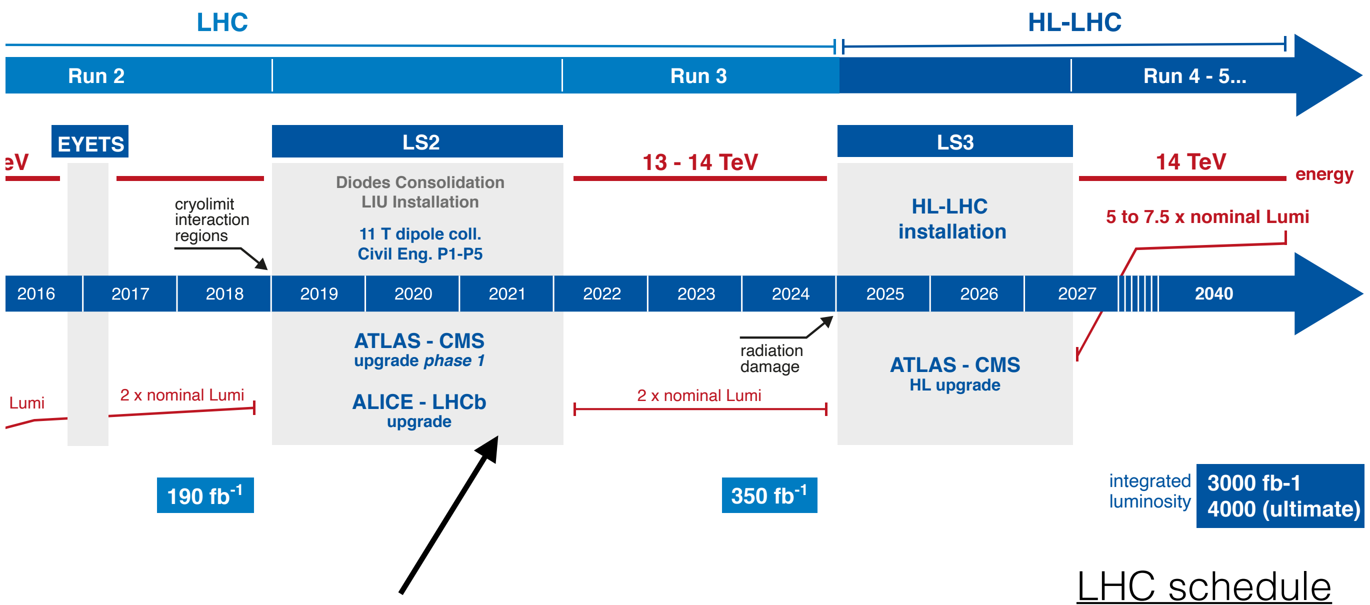
Sensitivity projection for future detectors

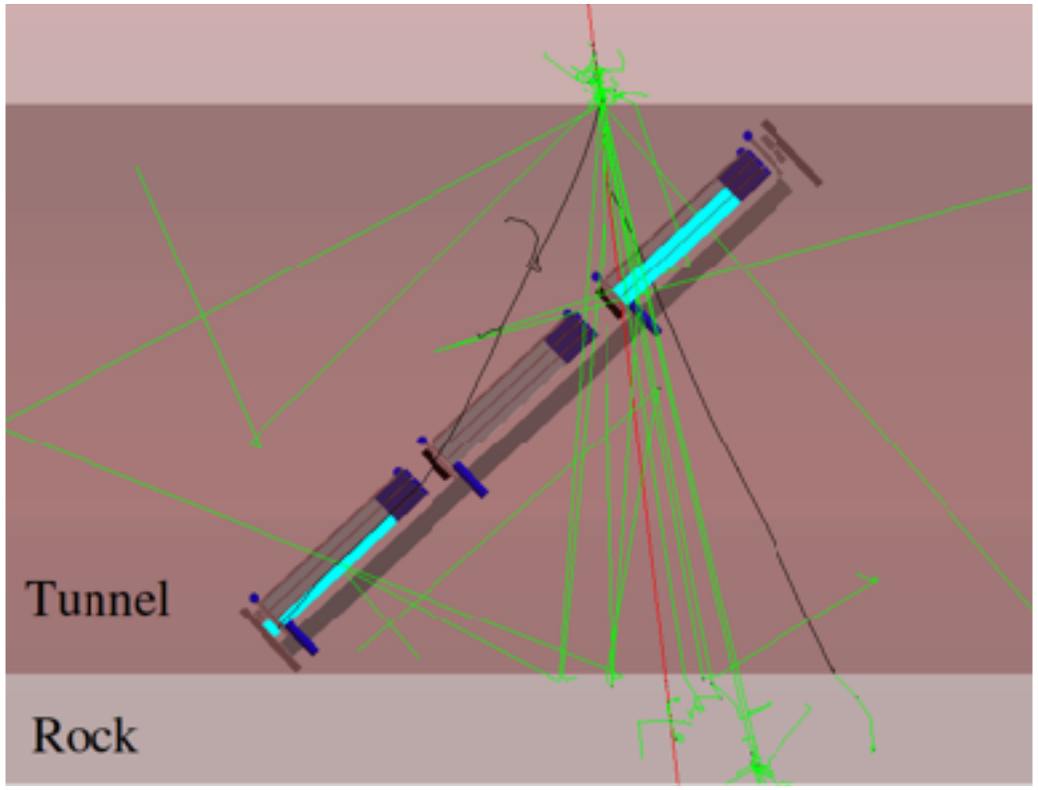


We are here

LHC schedule

- Use data from the demonstrator to update detector designs for Run 3 and the HL-LHC
- Robustly estimate signal performance and determine backgrounds
- Documented in projection paper submitted to PRD: https://arxiv.org/abs/2104.07151

- Important lesson: cosmic muon shower secondaries form substantial background
- Need **four layers** to reject overall background sufficiently to reach target sensitivity of 2016 LOI



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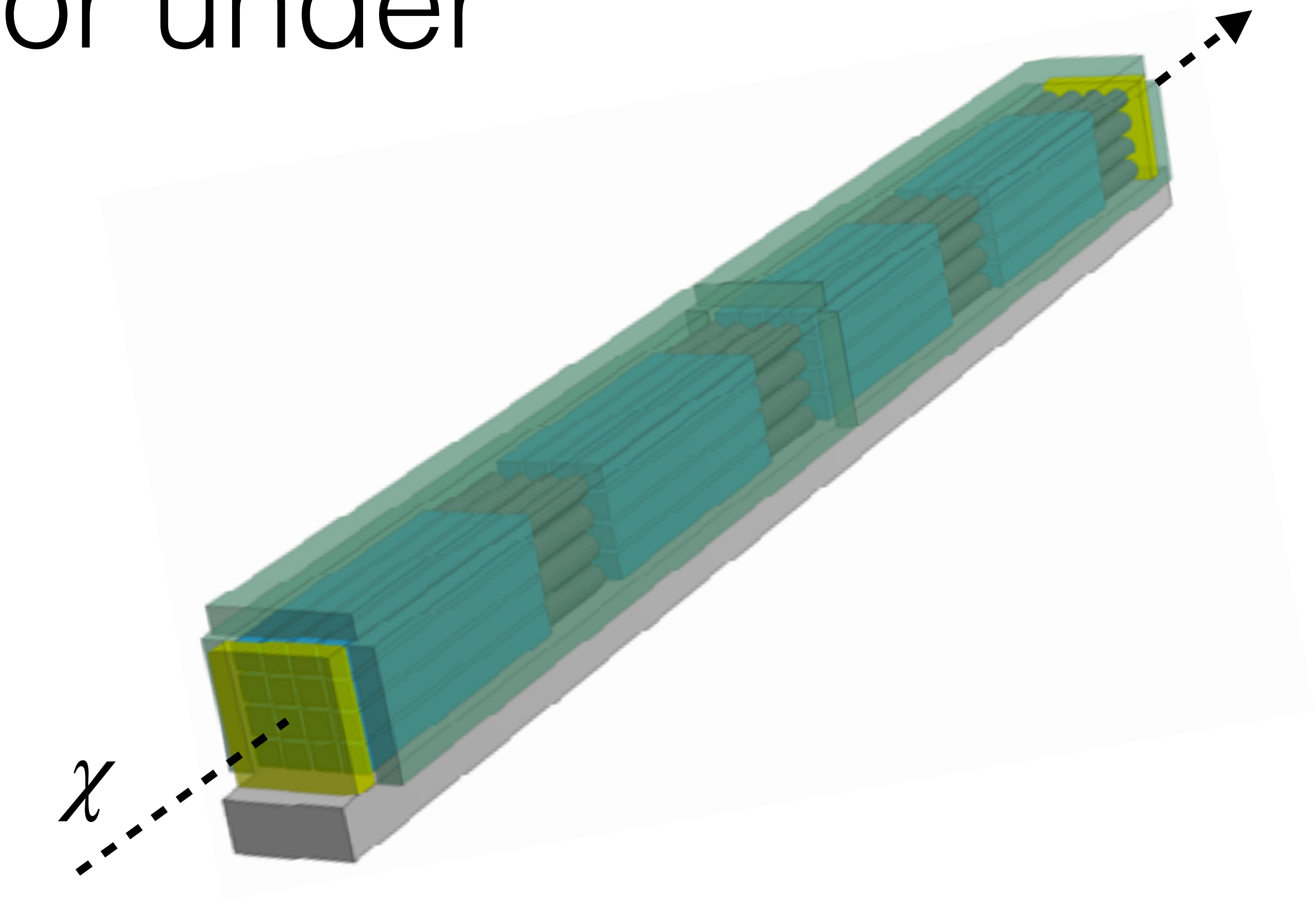
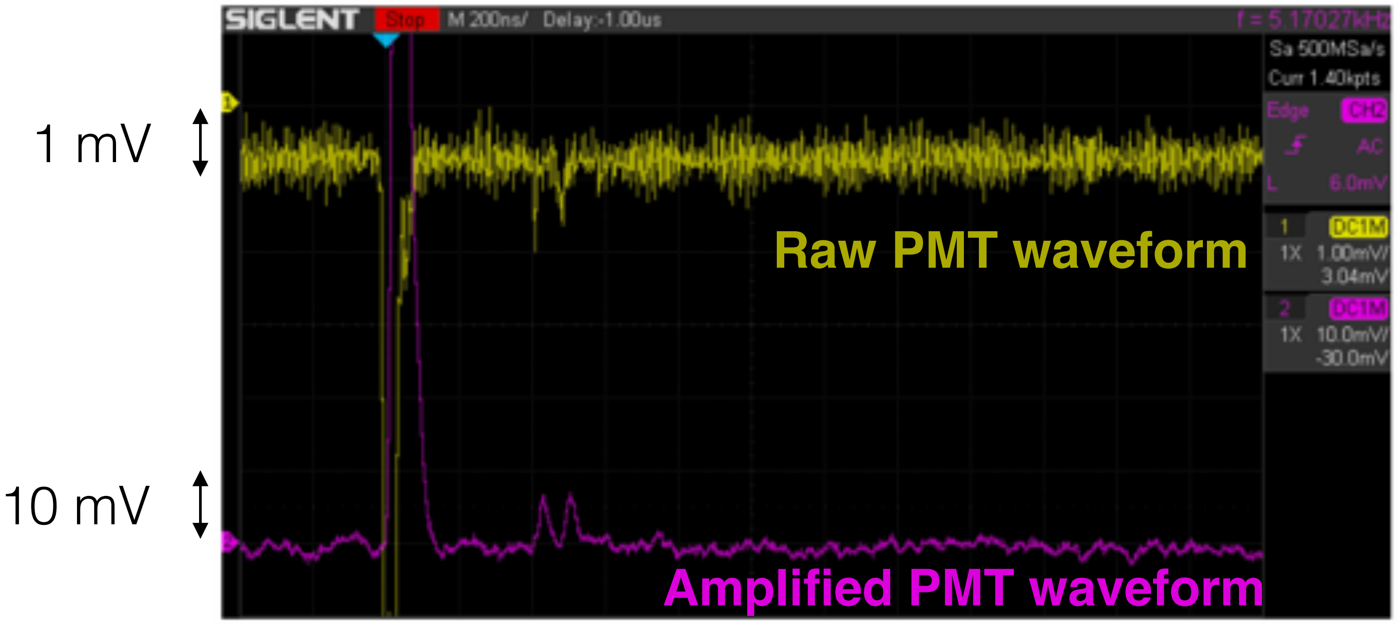
Run 3 milliQan detector under construction



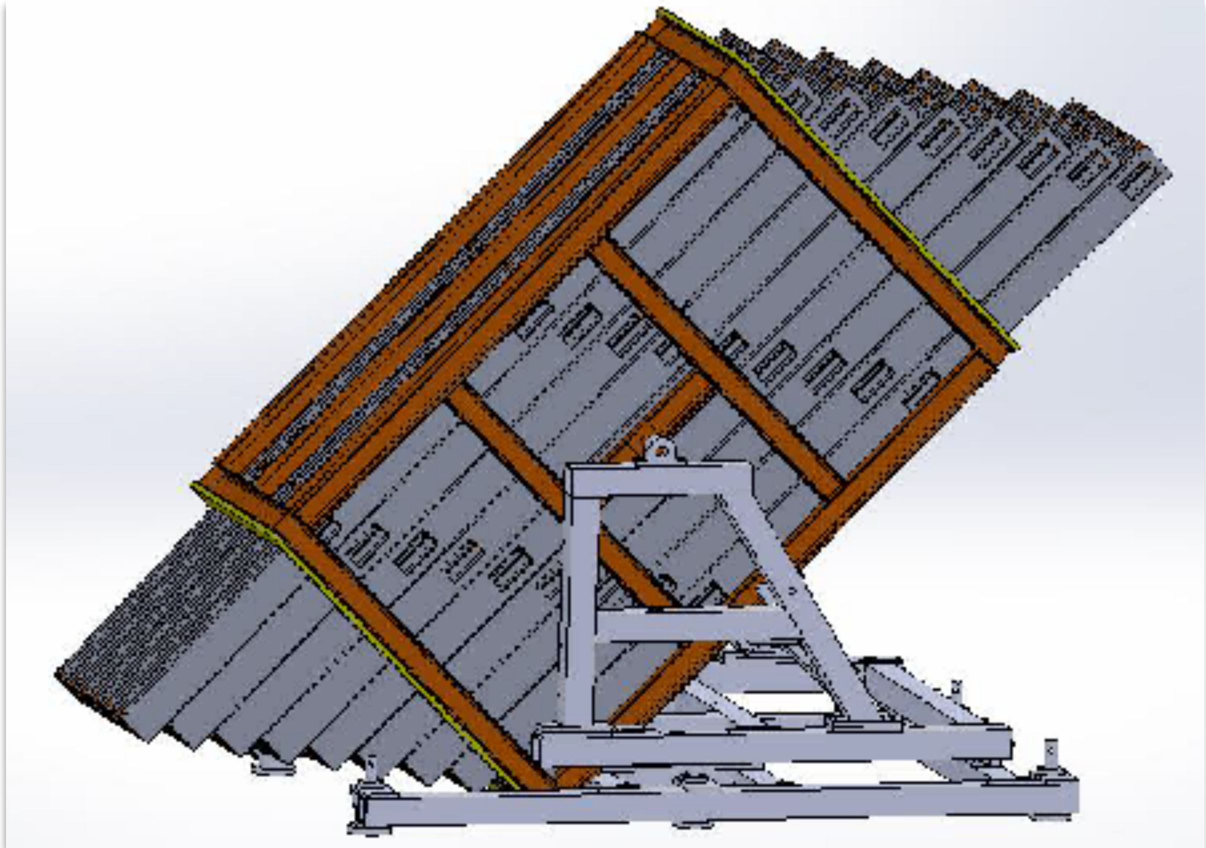
- **Funding secured** for Run 3 detector!
- **Four** layers of scintillator bars to control background from cosmic ray showers
- **Expanded size** of each layer (4x4 scintillator bars) to improve background rejection and increase signal acceptance
- Increased thickness of scintillator **veto** “panels/slab” to 5cm for improved shower tagging
- **Dedicated signal amplification** to improve reconstruction of very low energy deposits
- Make use of LED “flashers” and radioactive sources for improved response and timing calibrations



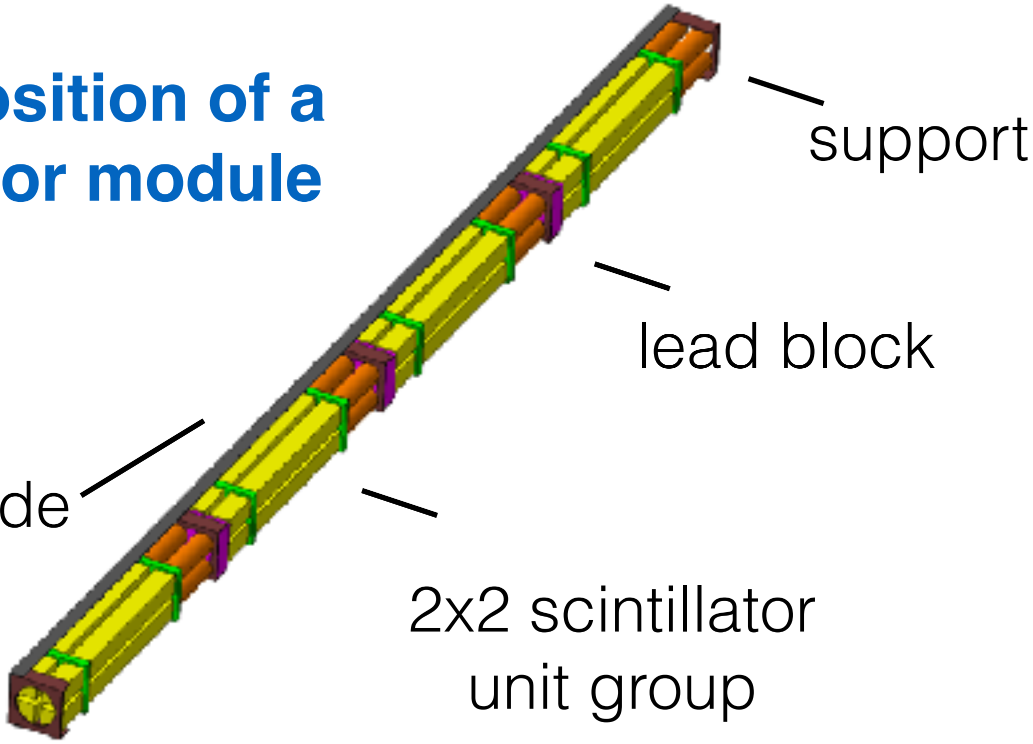
Signal amplification

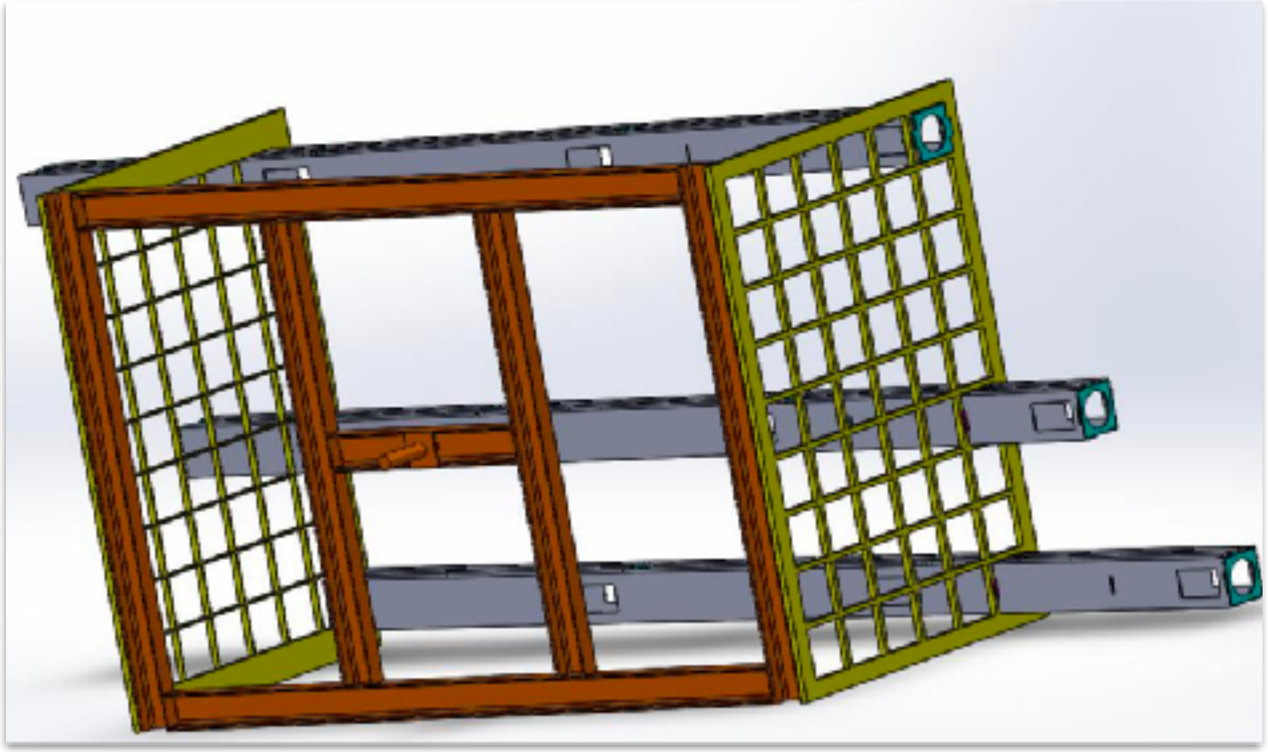
Detector for the HL-LHC

- Plans for mechanical structure mature
- Fit maximal number of bars into available space: 9x6x4x4 = 864 bars (1 x 1 x 3 m)
- Uses mount as in place in drainage gallery



Composition of a detector module





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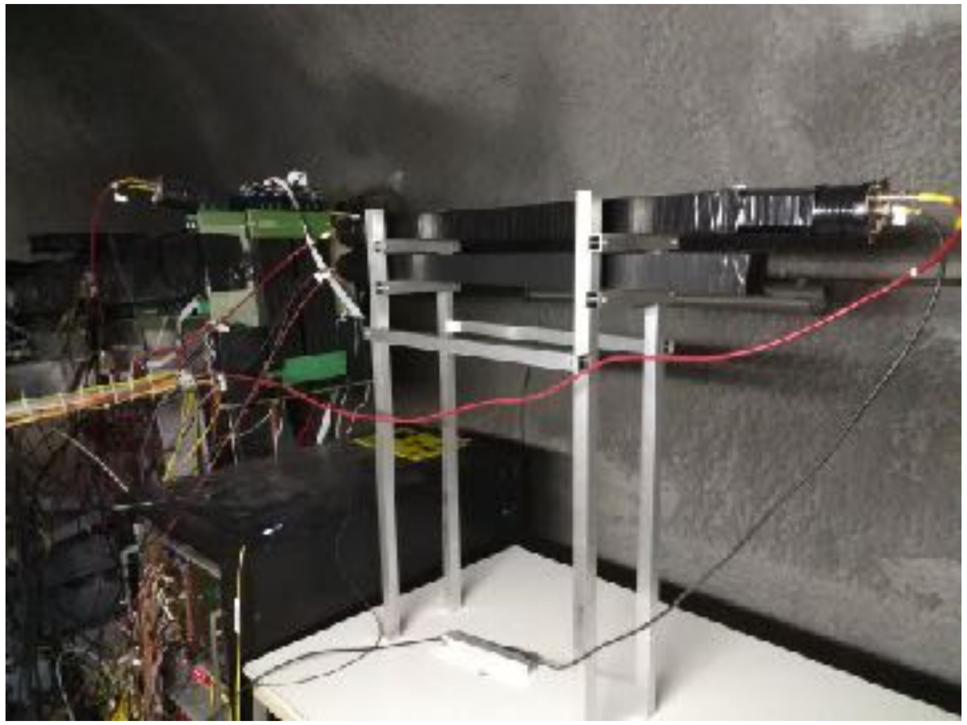
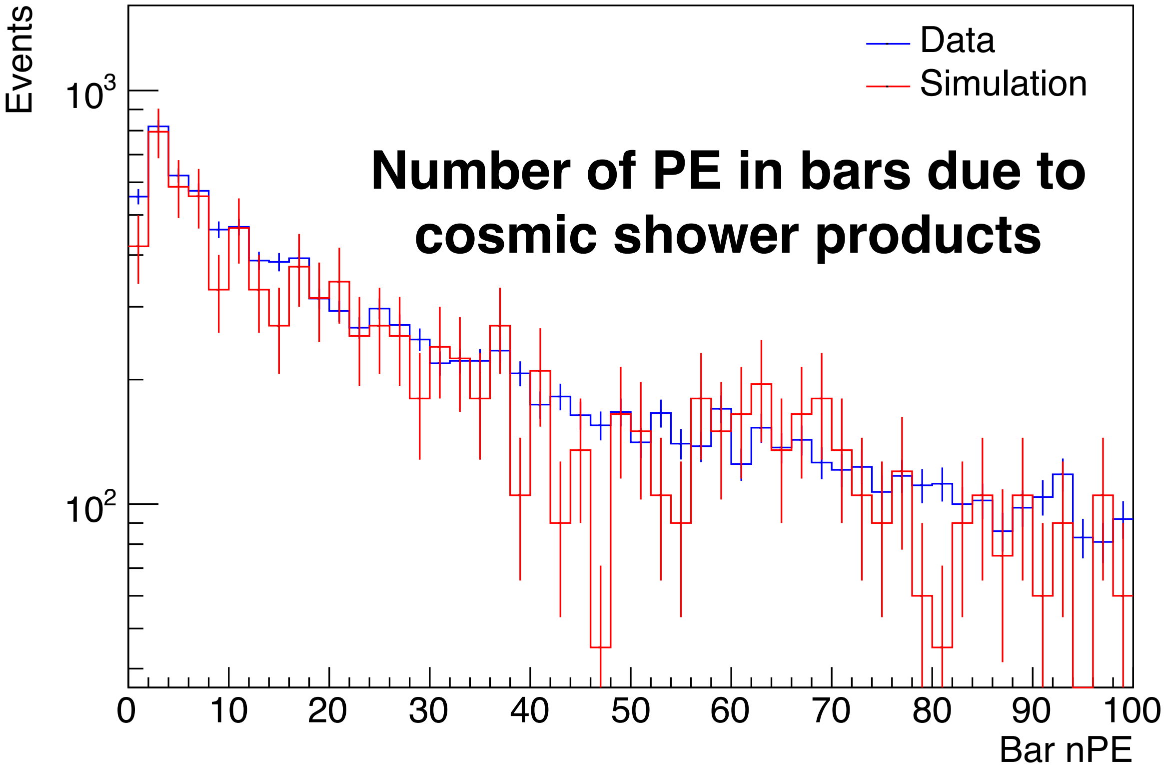
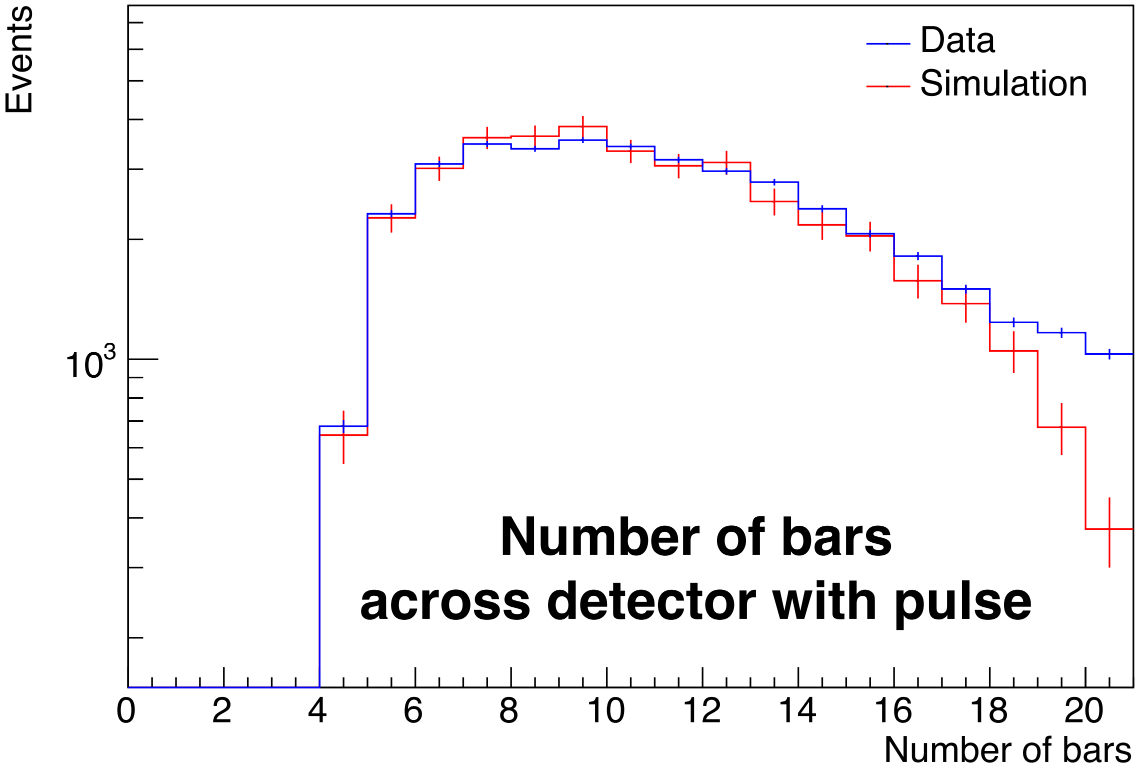
Cosmic background characterisation

- Cosmic muons propagated from surface (as for beam muons) and simulated with GEANT4
- Calibrate rate with “four layer” demonstrator data and compare modelling of crucial variables
- Cosmic shower background well described by simulation → **use calibrated simulation to estimate background rates** for full detectors



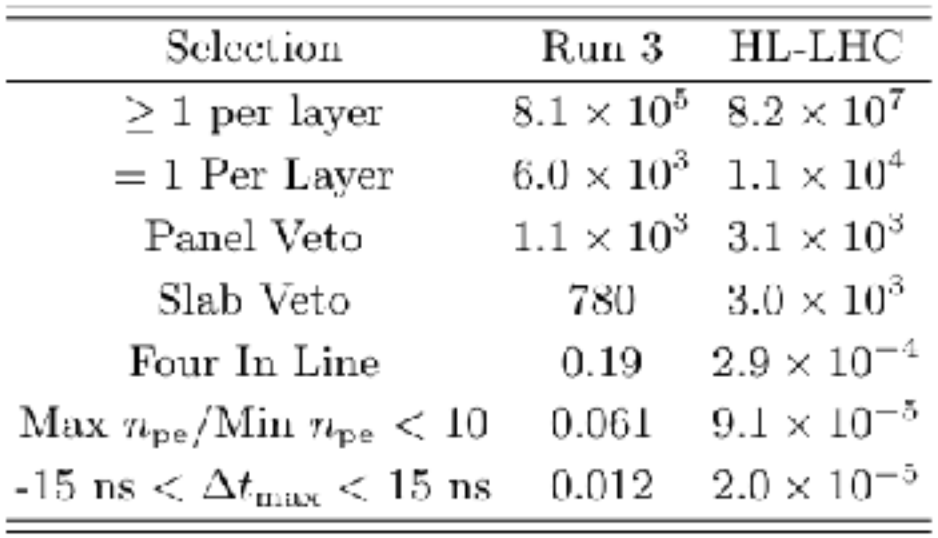


Number of PE in bars due to cosmic shower products



Number of bars across detector with pulse

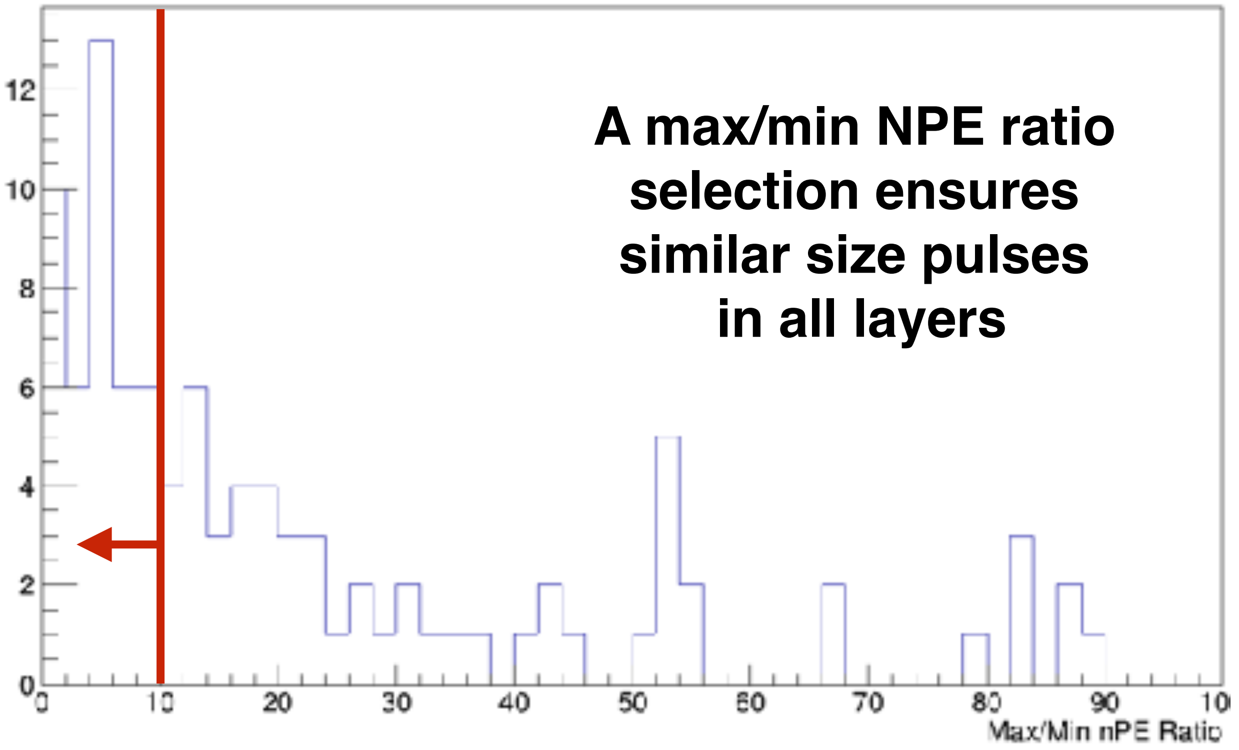
Background measurement



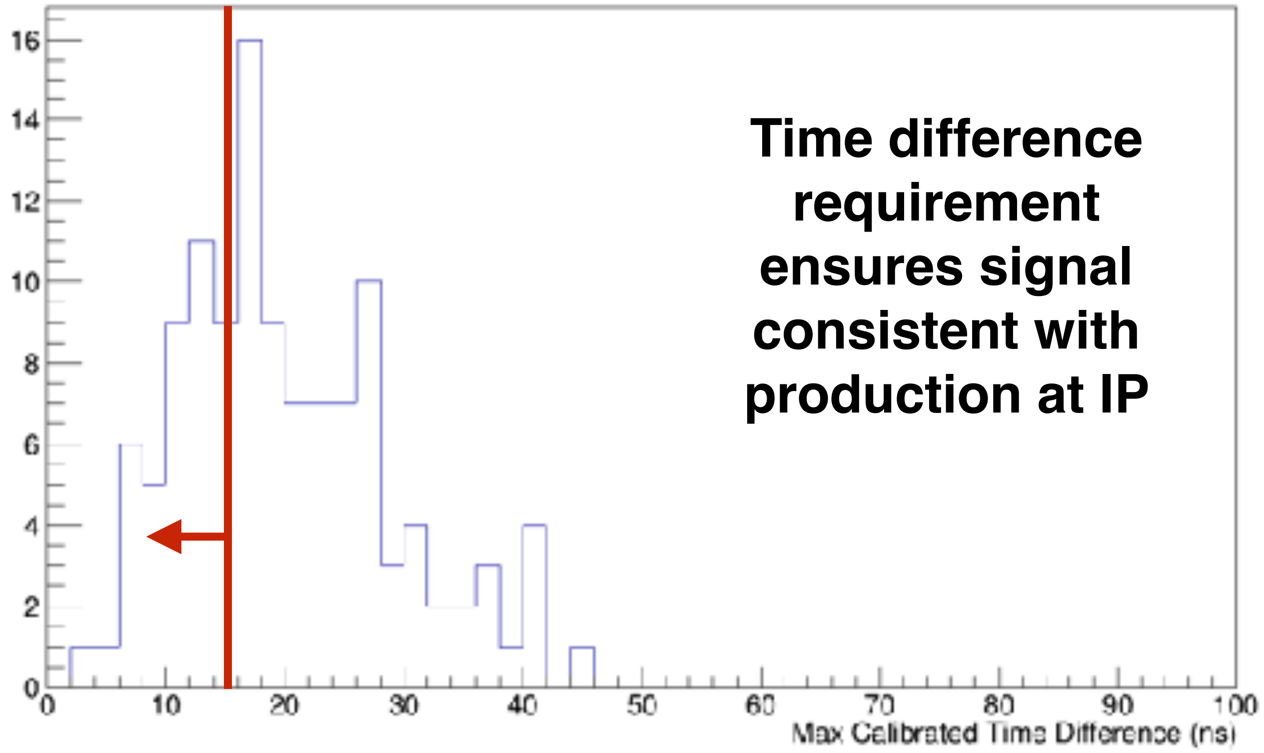
Selection	Run 3	HL-LHC
≥ 1 per layer	8.1×10^5	8.2×10^7
$= 1$ Per Layer	6.0×10^3	1.1×10^4
Panel Veto	1.1×10^3	3.1×10^3
Slab Veto	780	3.0×10^3
Four In Line	0.19	2.9×10^{-4}
Max n_{pe}/Min $n_{\mathrm{pe}} < 10$	0.061	9.1×10^{-5}
-15 ns $< \Delta t_{\mathrm{max}} <$ 15 ns	0.012	2.0×10^{-5}

+ background from dark-rate: expect 0.05/1.4 events in full Run 3/HL-LHC dataset

- Evaluate background using cosmic shower simulation that has been **calibrated and validated** with four layer demonstrator
- Selections motivated by Run 2 demonstrator search to reject backgrounds with high signal efficiency
- Once detector is installed will measure backgrounds directly in beam-off running and in beam-on control regions

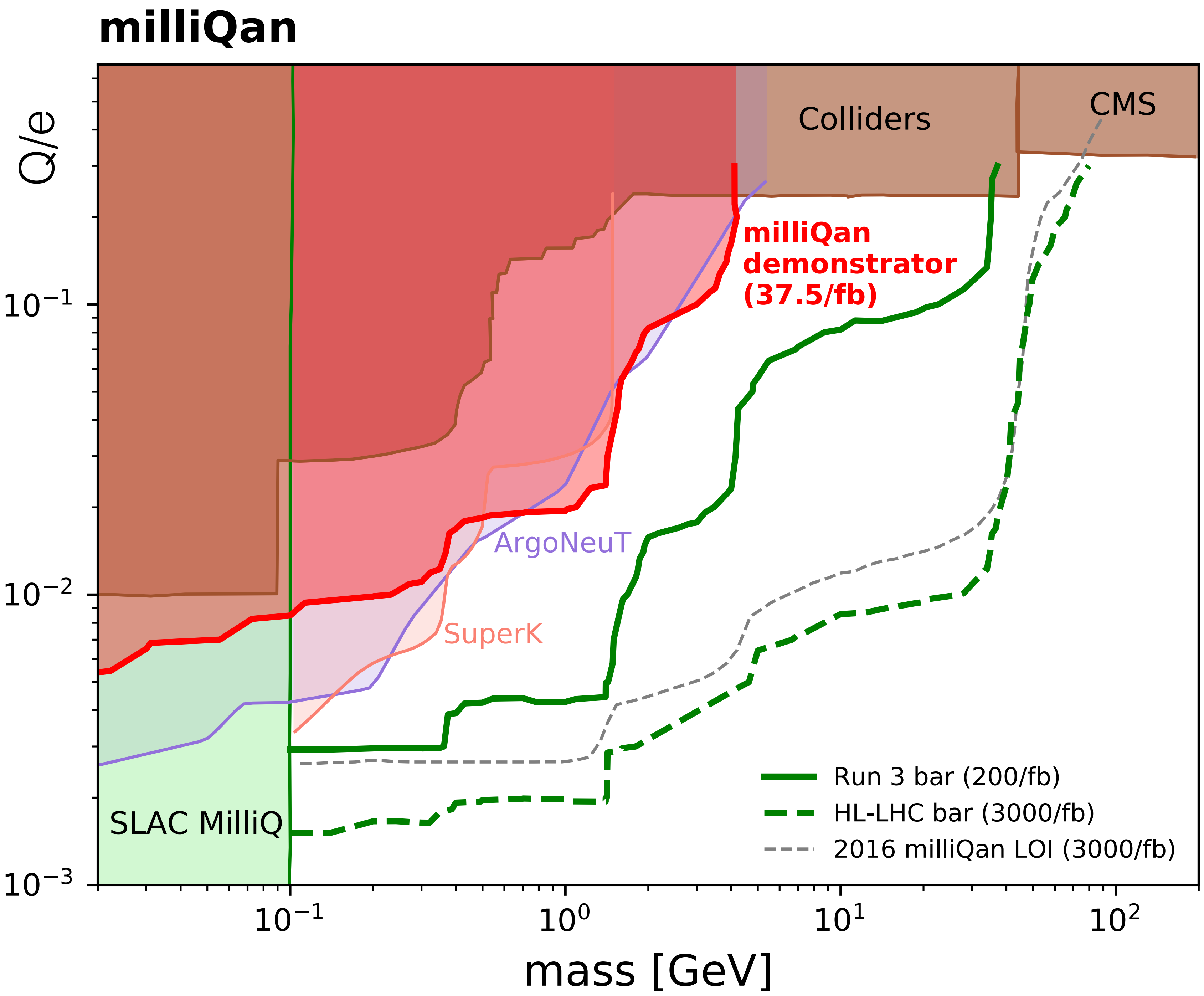


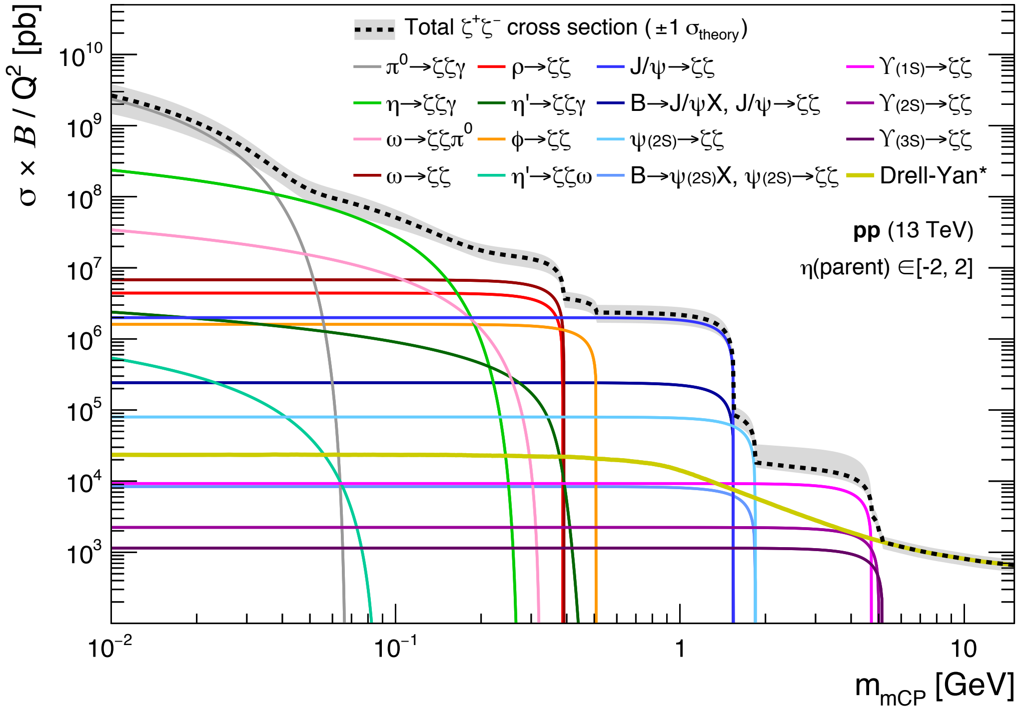
A max/min NPE ratio selection ensures similar size pulses in all layers



Time difference requirement ensures signal consistent with production at IP

Projections





- Wide range of signal production modes considered
- Signal efficiency evaluated with full GEANT4 detector simulation (calibrated with demonstrator data)
- Updated limit projections show Run 3 detector will **significantly expand reach**!
- Four layer HL-LHC detector **outperforms** 2016 LOI design

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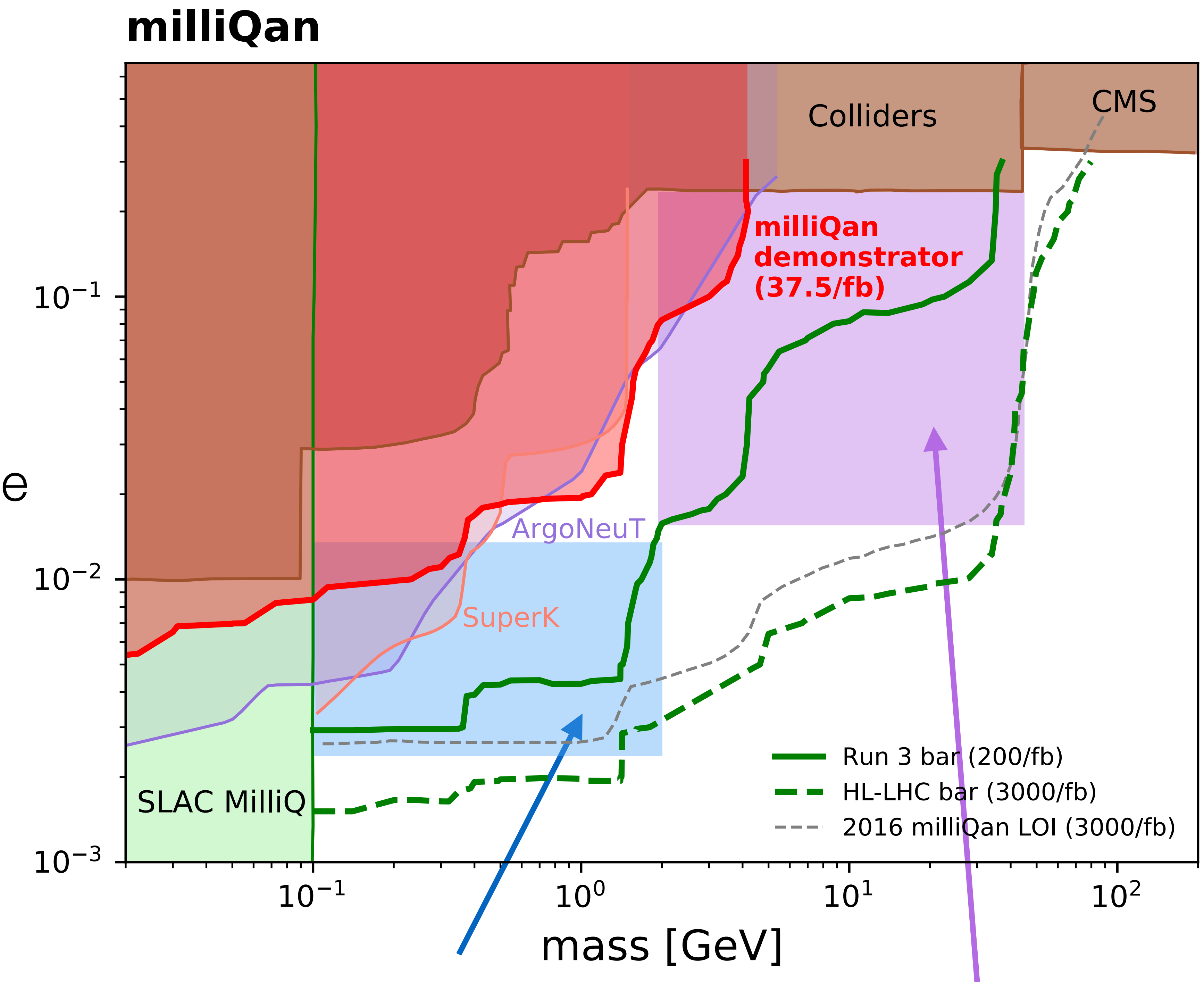
Optimising performance for Run 3

- Securing funding allows the freedom to explore new ideas
- For much of the phase space where milliqan drives sensitivity we are **acceptance limited**
- How to improve sensitivity in this regime?
- Use “slabs” to cover maximum area for low cost!



Charge limited region: very high mcp flux but low efficiency

Acceptance limited region: high efficiency but mcp flux is low

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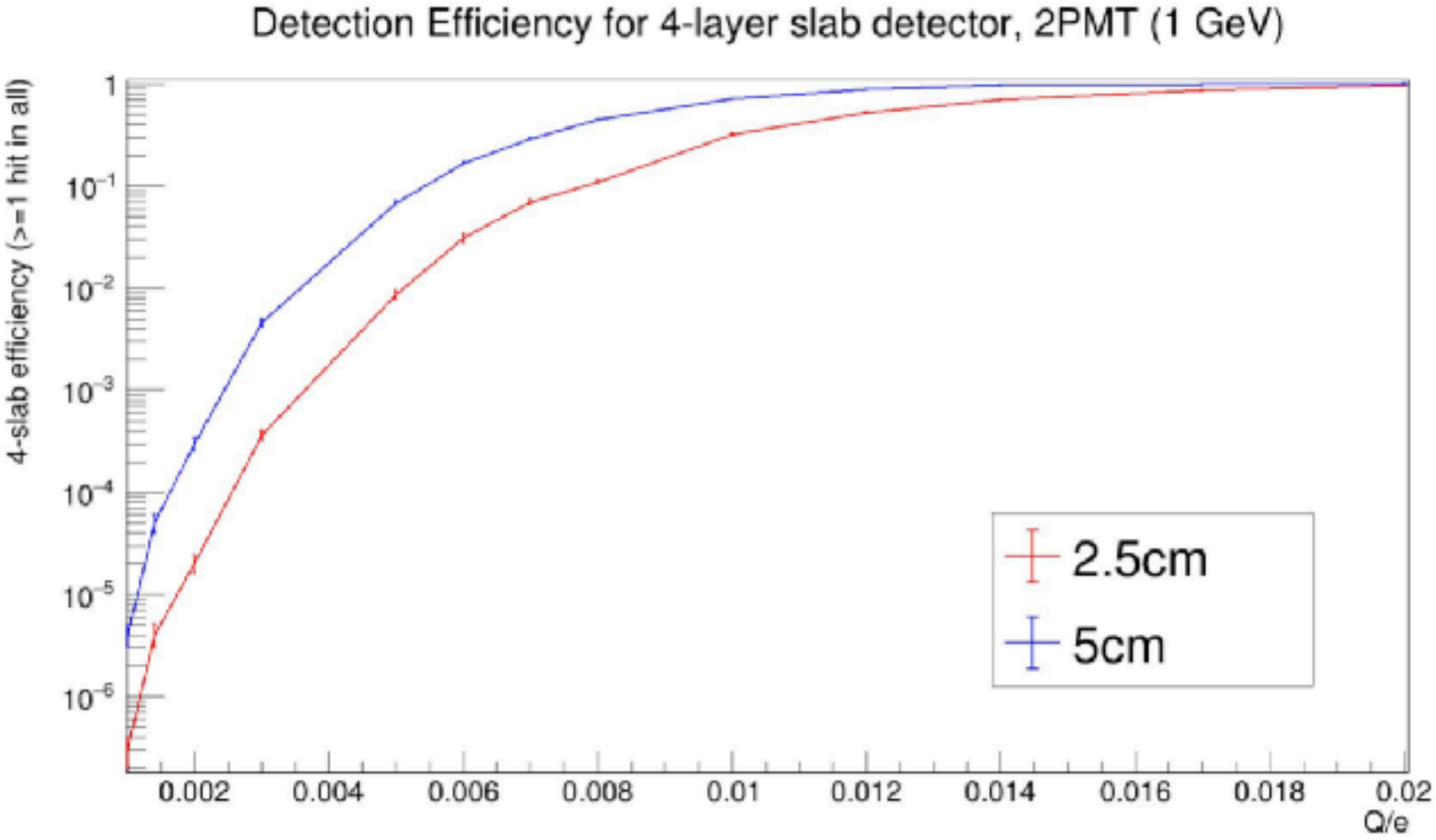
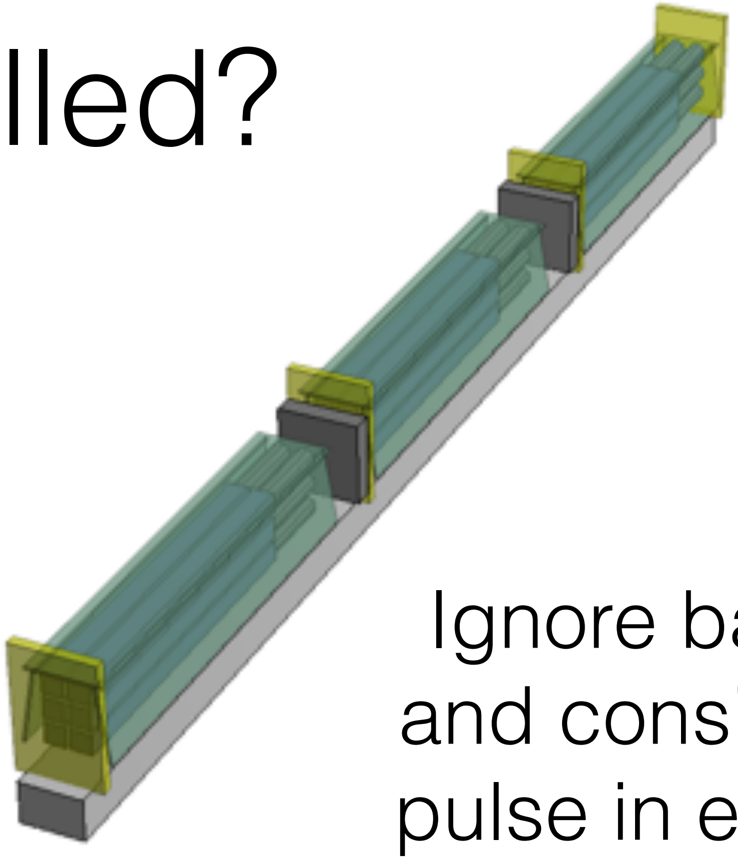
How low in charge are slabs sensitive?

- Simulate mcps of various charges travelling through slabs and plot probability for ≥1 photon **detected** in all 4 layers
- Efficient for targeted region of Q > 0.01 with **5cm thick slabs**
- What about backgrounds? Look at the demonstrator data

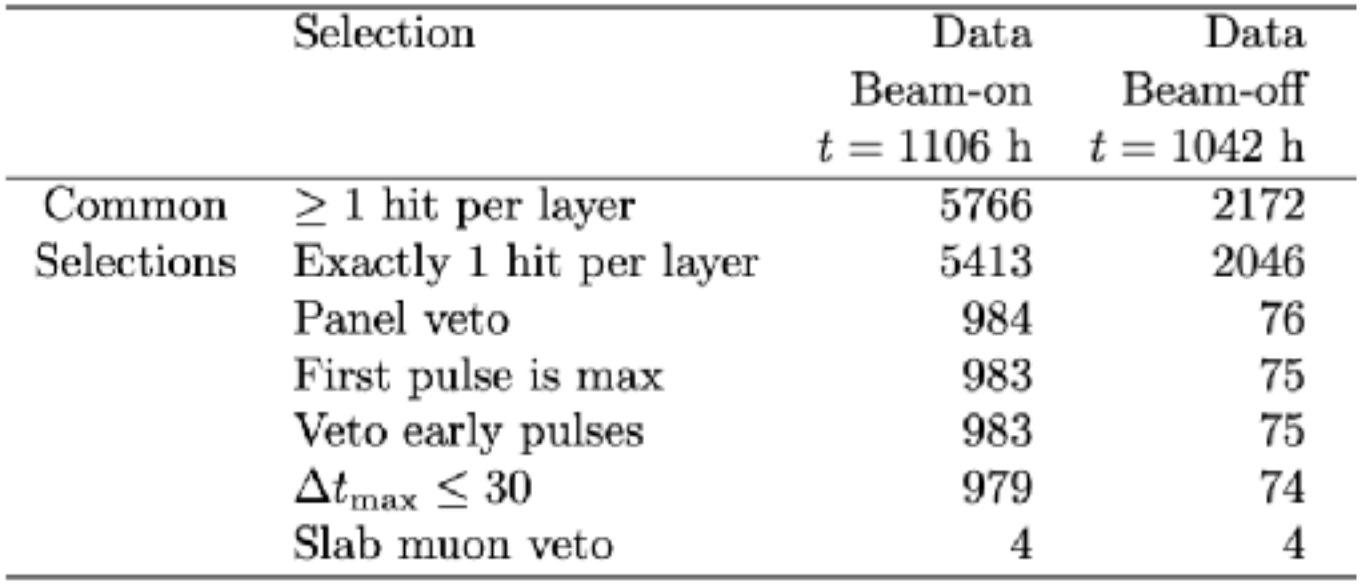


20x30cm slab face

Can backgrounds be controlled?



Measure “4 layer slab” background rates in demonstrator data



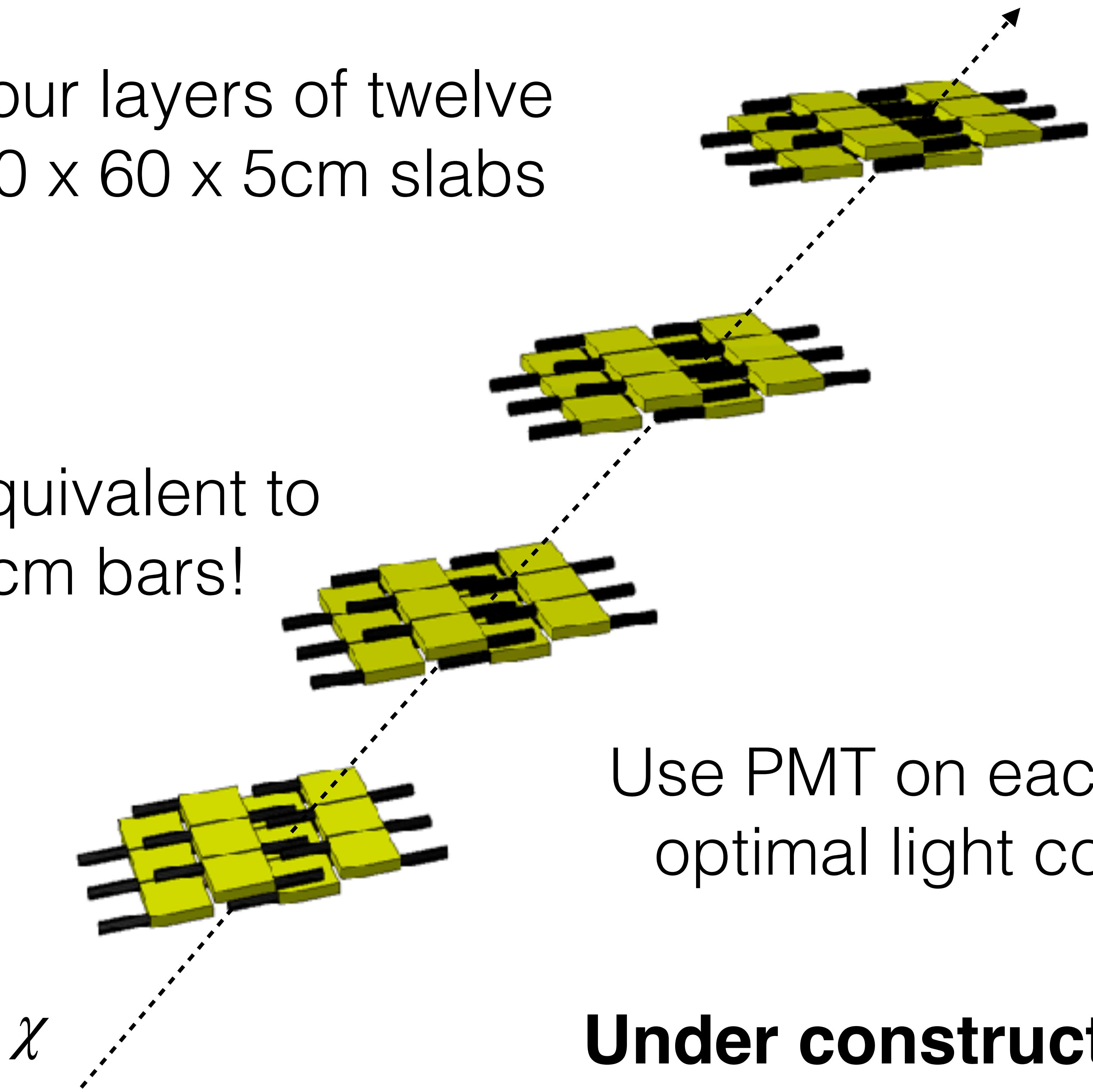
	Selection	Data Beam-on $t = 1106$ h	Data Beam-off $t = 1042$ h
Common Selections	≥ 1 hit per layer	5766	2172
	Exactly 1 hit per layer	5413	2046
	Panel veto	984	76
	First pulse is max	983	75
	Veto early pulses	983	75
	$\Delta t_{\mathrm{max}} \leq 30$	979	74
	Slab muon veto	4	4

Ignore bars and consider pulse in each of 4 slabs

Backgrounds can be effectively rejected without the bars!

Motivates the Run 3 milliQan slab detector!

The Run 3 milliQan slab detector



Four layers of twelve
40 x 60 x 5cm slabs

Surface area equivalent to
~**1100** 5 x 5cm bars!

Use PMT on each end for
optimal light collection

Under construction now!

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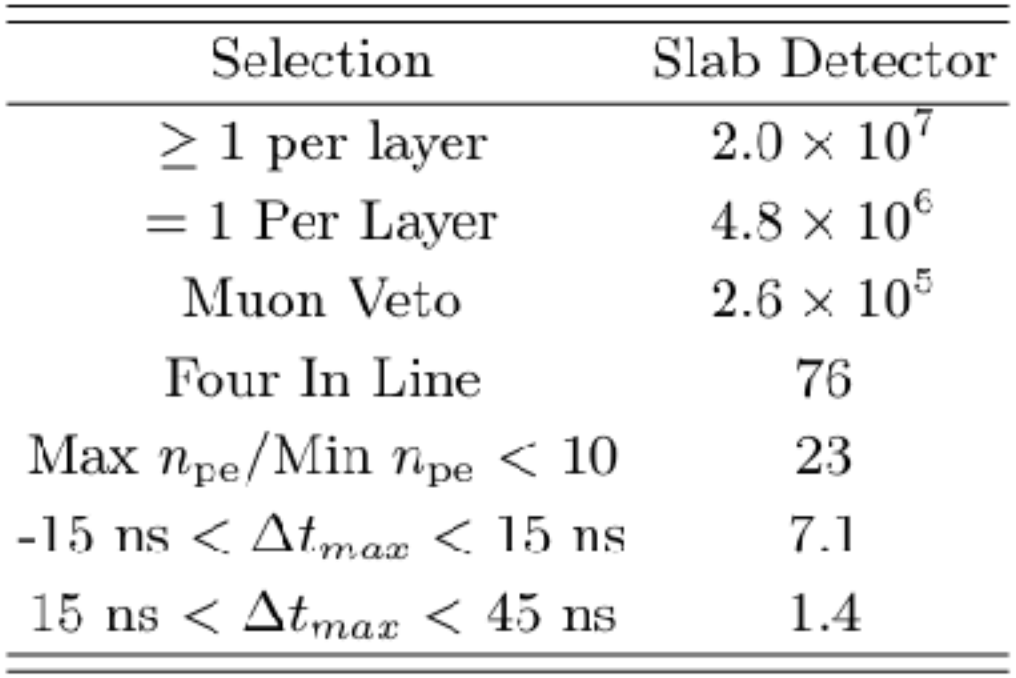
Full background consideration

- Evaluate background with fully validated cosmic simulation (as for bar detector)
- Use additional “high time” signal region to improve performance near resonance mass thresholds (where mcp β < 1)
- Using 4 layers, achieve low background in both regions
- Confirm with in-situ measurements - modular design easy to alter if required!



Selection	Slab Detector
≥ 1 per layer	2.0×10^7
$= 1$ Per Layer	4.8×10^6
Muon Veto	2.6×10^5
Four In Line	76
Max n_{pe}/Min $n_{\mathrm{pe}} < 10$	23
-15 ns $< \Delta t_{max} <$ 15 ns	7.1
15 ns $< \Delta t_{max} <$ 45 ns	1.4

+ background from dark-rate: expect 0.03 (|Δt| < 15)/ 0.7 (15 < Δt < 45) events in full Run 3 dataset

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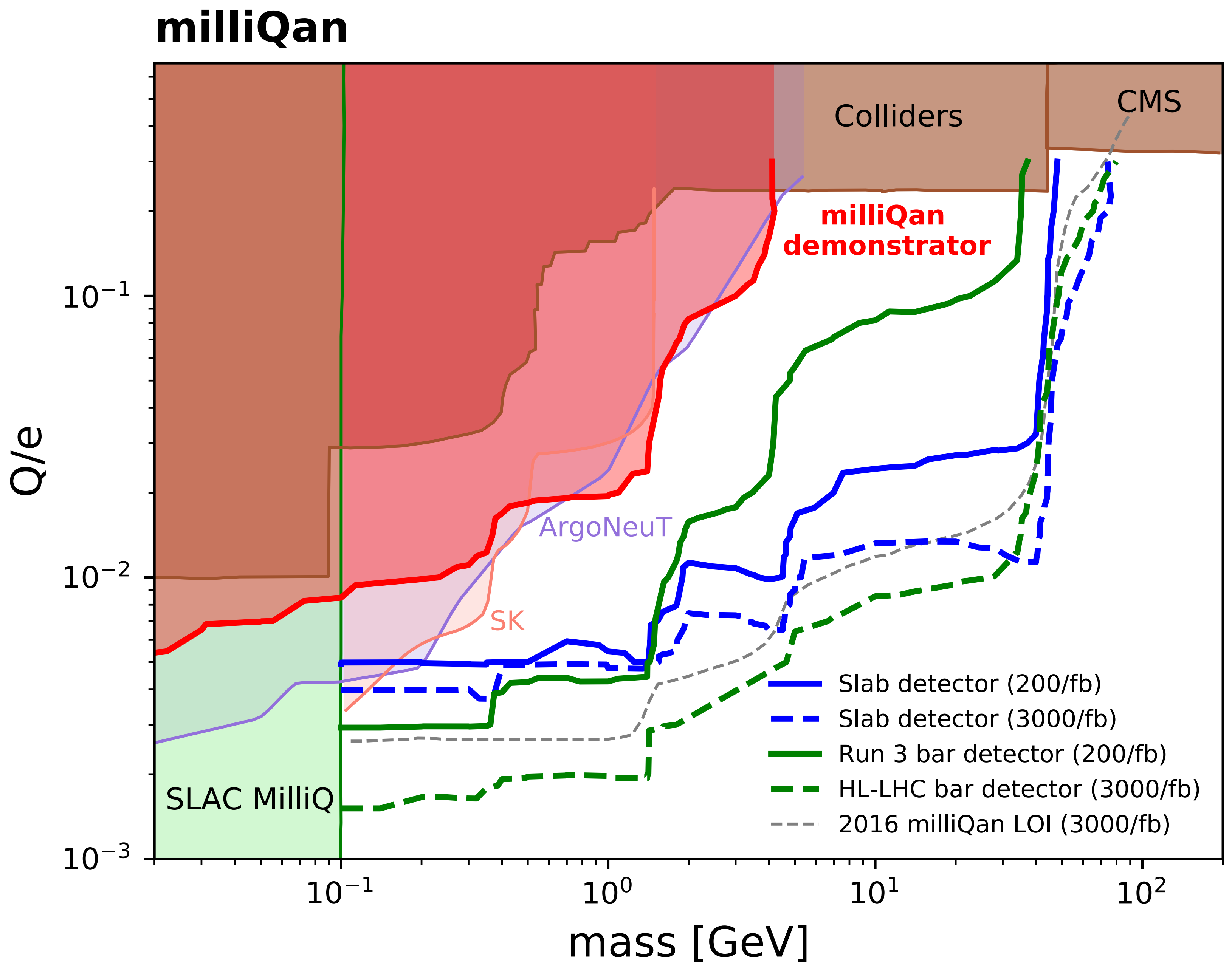
Sensitivity

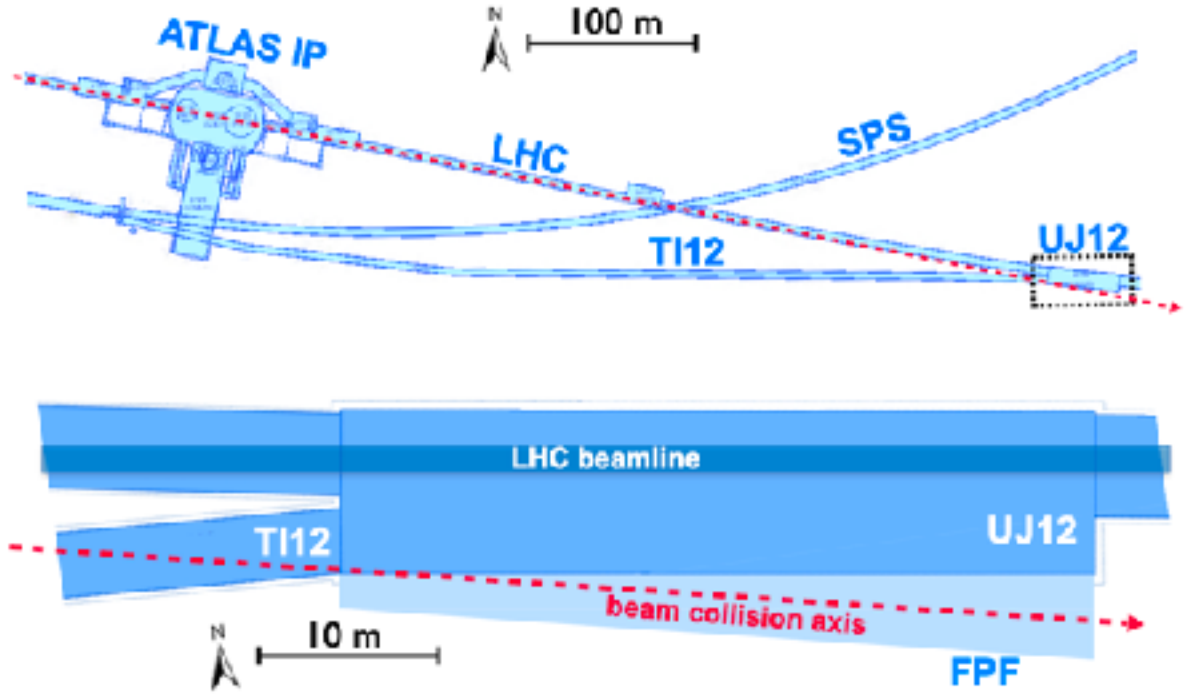


- Slab detector gives sensitivity to $Q \lesssim 0.02e$ for $m < m_Z/2$
- Experimental design backed up by **guaranteed physics** from bar detector
- Expect world leading sensitivity for **0.1 < m < 45 GeV** using combination of slab and bar detector

More details: https://arxiv.org/abs/2104.07151

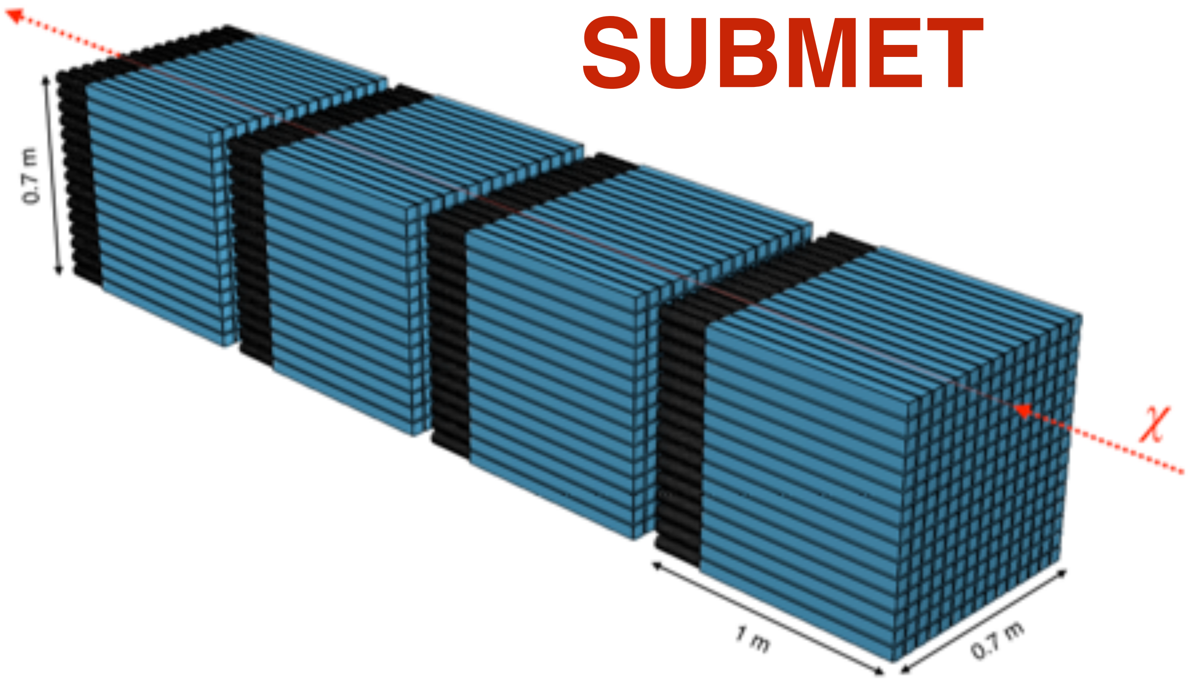
Beyond milliQan

FORMOSA



Forward region of **LHC** with sensitivity for m < ~80 GeV 2010.07941

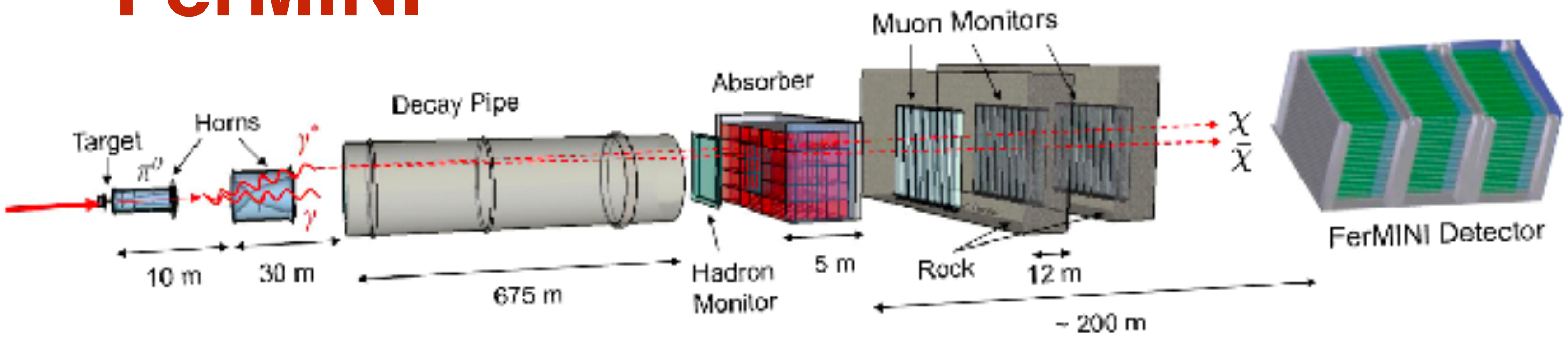
SUBMET



J-PARC with sensitivity for m < ~1.5 GeV

2007.06329

FerMINI



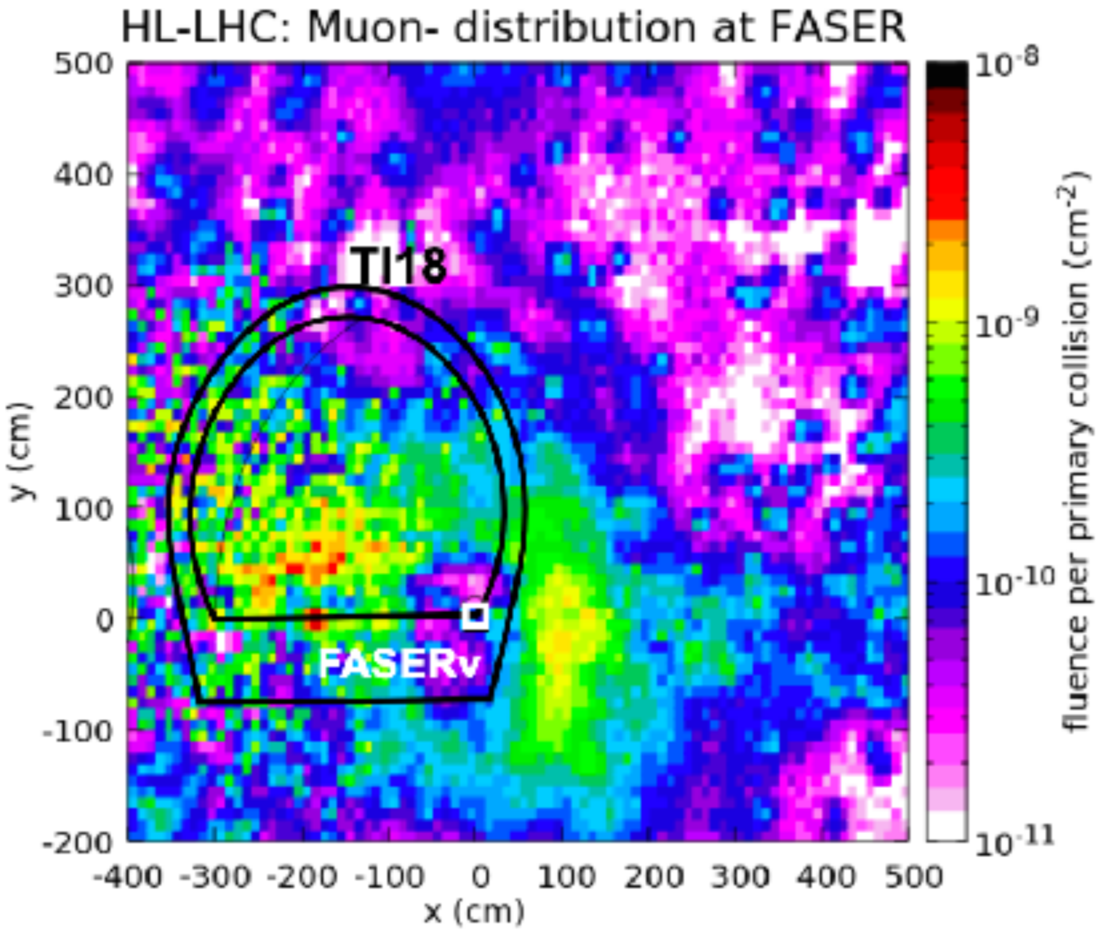
Fermilab with sensitivity for m < ~5 GeV

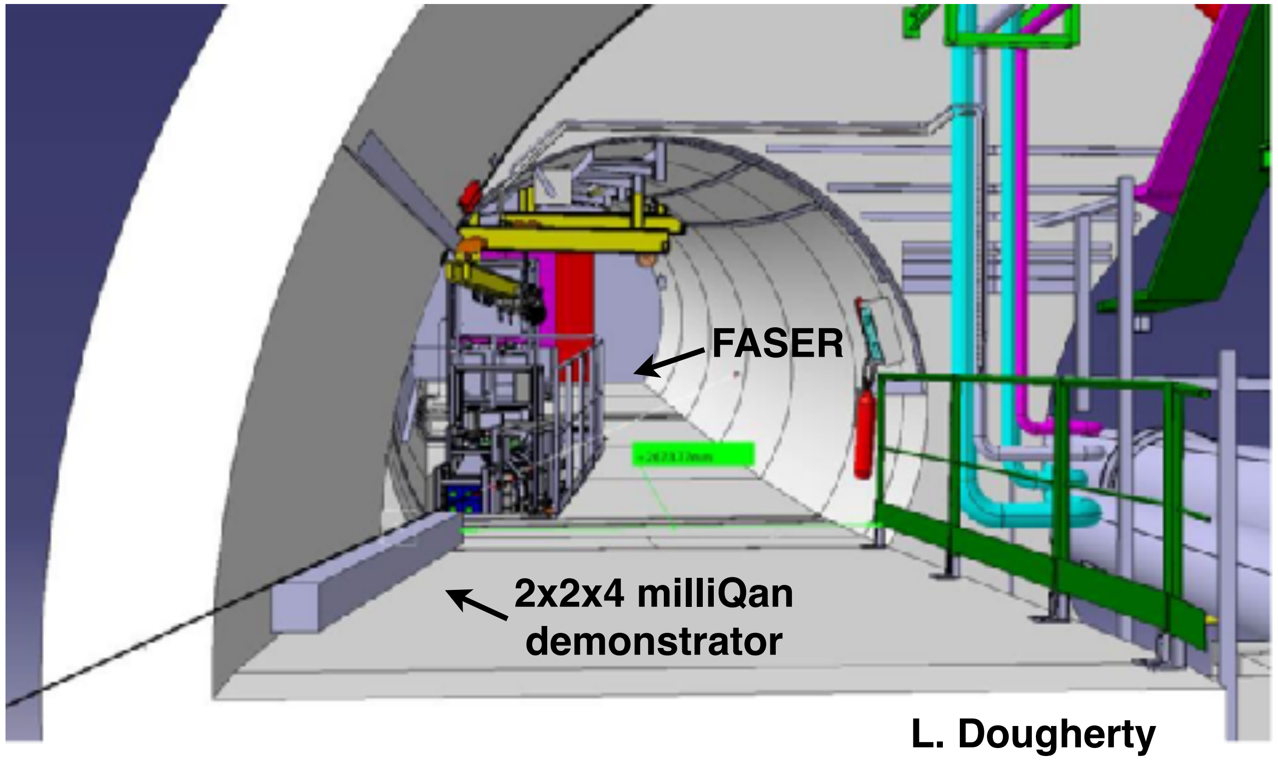
1812.03998

Range of detectors with same basic design provide **complementary sensitivity**

Focus on FORMOSA

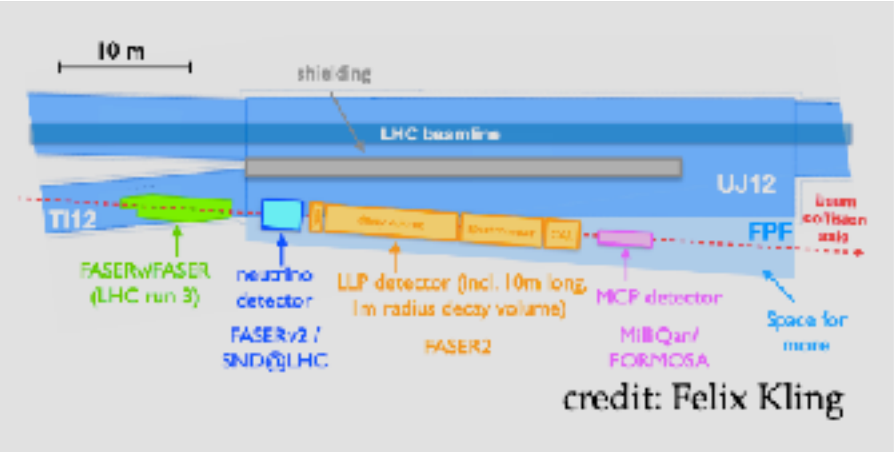
- FORMOSA proposal: forward detector could see up to factor ~ 250 higher mcp rate compared to central location
- Challenge: through-going muon flux > ~**1 Hz/cm²** (current location: ~0.05 Hz/cm²)
- Beam muons provide significant challenges to trigger and background rejection (from afterpulses)
  - is a detector feasible in this location?





L. Dougherty

- Exploring possibility (with FASER collaboration) to study forward backgrounds with Run 2 milliQan demonstrator in UJ12
- Longer term: place larger detector in proposed Forward Physics Facility



credit: Felix Kling

FORMOSA proposal (S. Foroughi-Abari, F. Kling, Y. Tsai)

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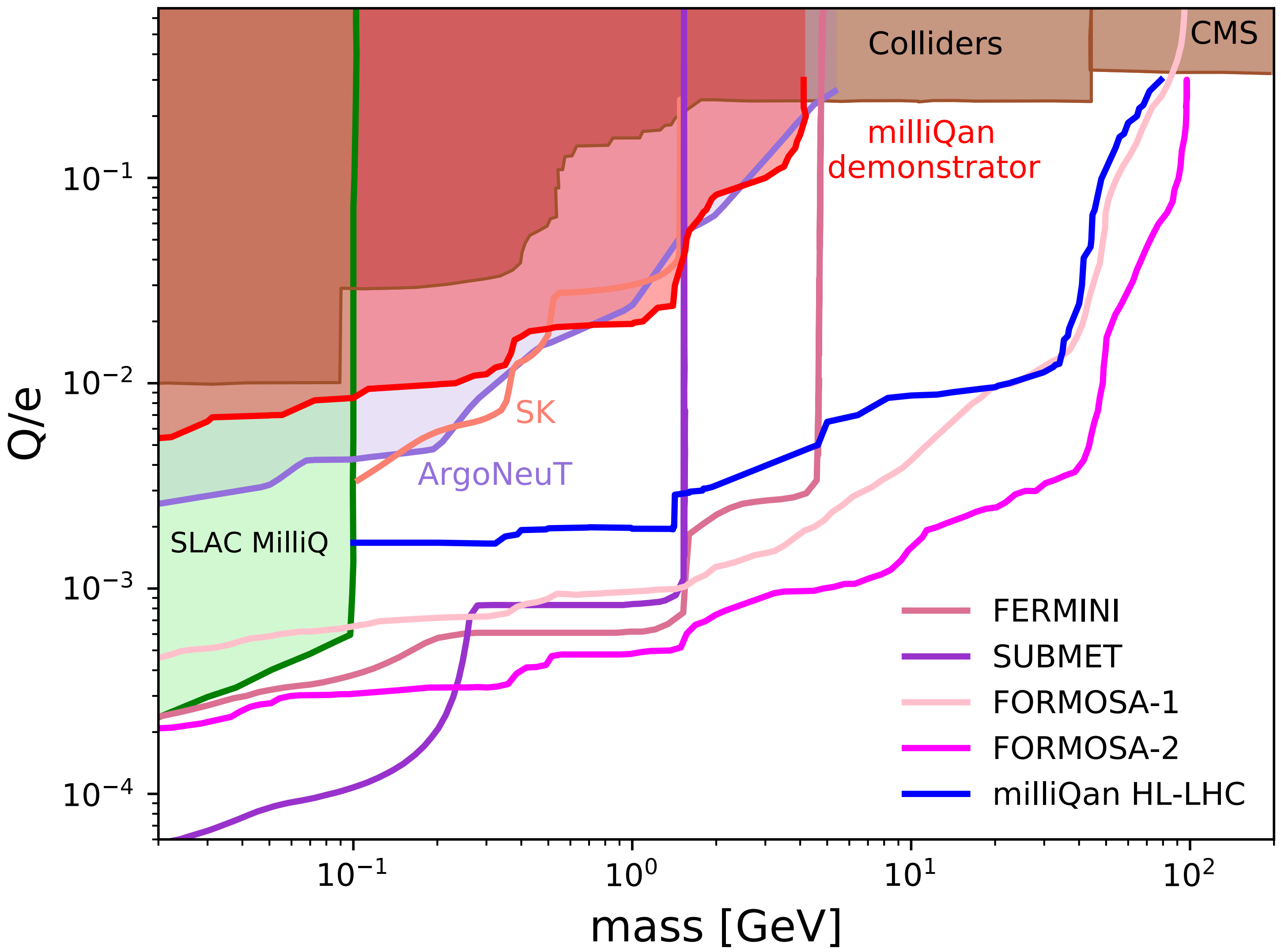
Sensitivities



- Complementary sensitivity from detectors at range of facilities
- Forward regime at the LHC provides very exciting sensitivity prospects **if** backgrounds can be controlled!
- Demonstrator results **key** in proving feasibility of all proposals!
- Exploring further for snowmass - see LOIs here and here

Sources

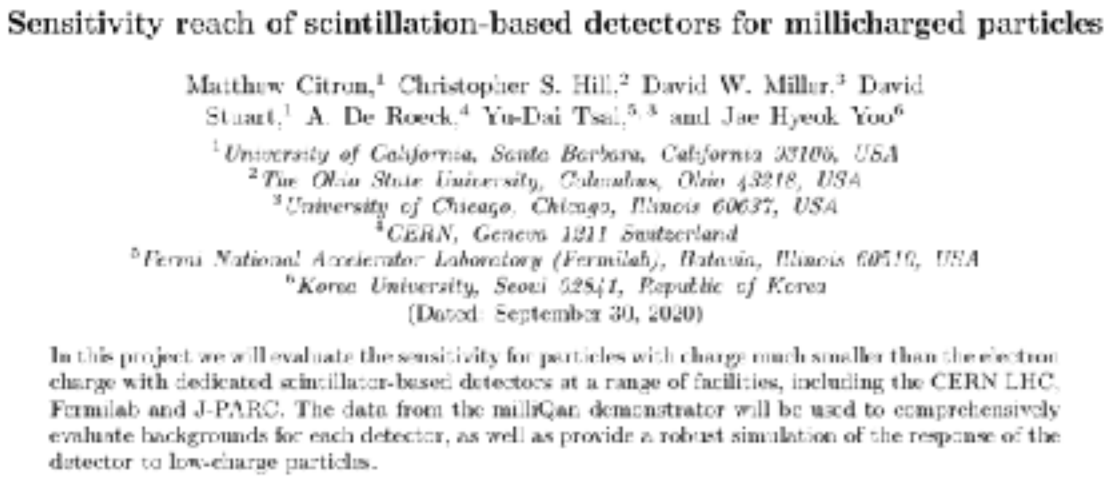
FORMOSA: 2102.11493

SUBMET: 2007.06329

FERMINI: 1812.03998

milliQan: 2104.07151

Major caveat: FORMOSA lines assume efficient triggering and rejection of beam muon induced backgrounds



Sensitivity reach of scintillation-based detectors for millicharged particles

Matthew Citron,[1] Christopher S. Hill,[2] David W. Miller,[3] David Stuart,[1] A. De Roeck,[4] Yu-Dai Tsai,[5, 3] and Jae Hyeok Yoo[6]

[1] *University of California, Santa Barbara, California 93106, USA*
[2] *The Ohio State University, Columbus, Ohio 43210, USA*
[3] *University of Chicago, Chicago, Illinois 60637, USA*
[4] *CERN, Geneva 1211 Switzerland*
[5] *Fermi National Accelerator Laboratory (Fermilab), Batavia, Illinois 60510, USA*
[6] *Korea University, Seoul 02841, Republic of Korea*
(Dated: September 30, 2020)

In this project we will evaluate the sensitivity for particles with charge much smaller than the electron charge with dedicated scintillator-based detectors at a range of facilities, including the CERN LHC, Fermilab and J-PARC. The data from the milliQan demonstrator will be used to comprehensively evaluate backgrounds for each detector, as well as provide a robust simulation of the response of the detector to low-charge particles.

Summary

- The milliQan demonstrator ran very successfully through 2018 with important insights gained for future detectors

- With data from the demonstrator have robustly estimated dominant **backgrounds** and signal performance for future detectors at the LHC (projection paper coming soon!)

- Constructing new milliQan bar and slab detectors for Run 3 **now** with excellent discovery prospects!

- Exciting opportunities for a range of complementary scintillator based detectors at the LHC, Fermilab and J-PARC

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milliQan collaboration

C. Hill, B. Francis,
M. Carrigan, L. Lavezzo,
B. Manley

A. Haas,
M. Ghimire

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

D. Miller,
M. Swiatlowski

S. Lowette

Y-D. Tsai

M. Ezzeldine,
J. Sahili, H. Zaraket,

F. Golf

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

J. Brooke,
J. Goldstein

This speaker supported by
funding from DOE Office of Science

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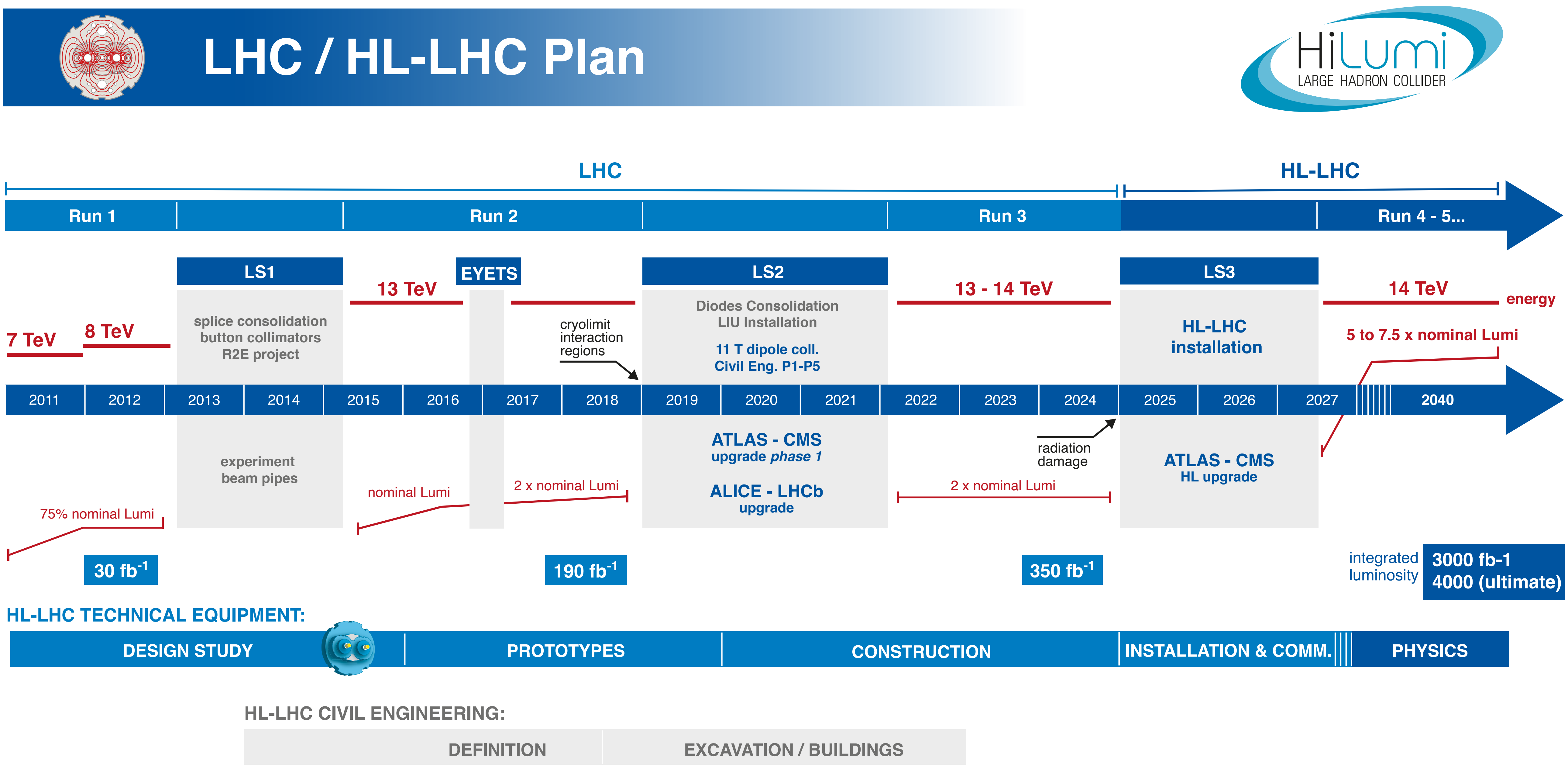
Backup

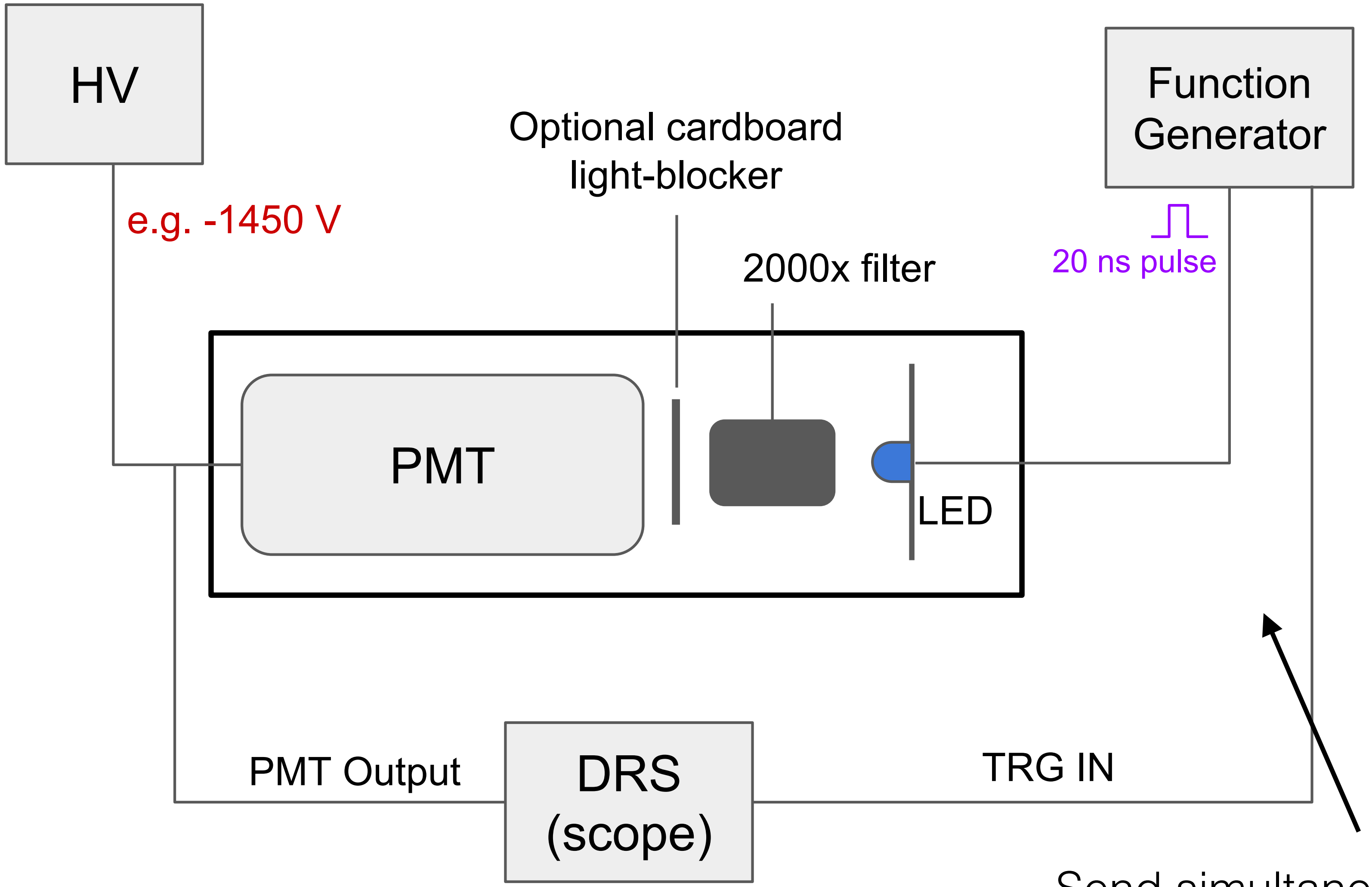
LHC schedule



https://project-hl-lhc-industry.web.cern.ch/sites/project-hl-lhc-industry.web.cern.ch/files/inline-images/HL-LHC-plan-2020-Plan-2.pdf

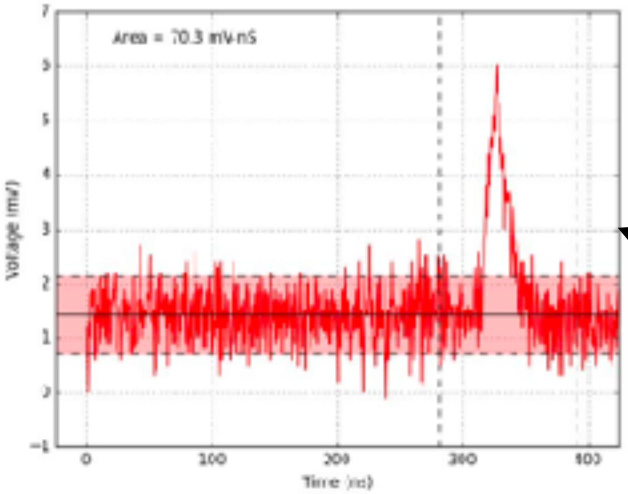
SPE calibration using LED

3D-printed casing to hold PMT, LED, filters



Send simultaneous LED pulse and trigger

Digitise and record waveforms



Measure pulse area using integral of window

Will show results for example PMT (R878)

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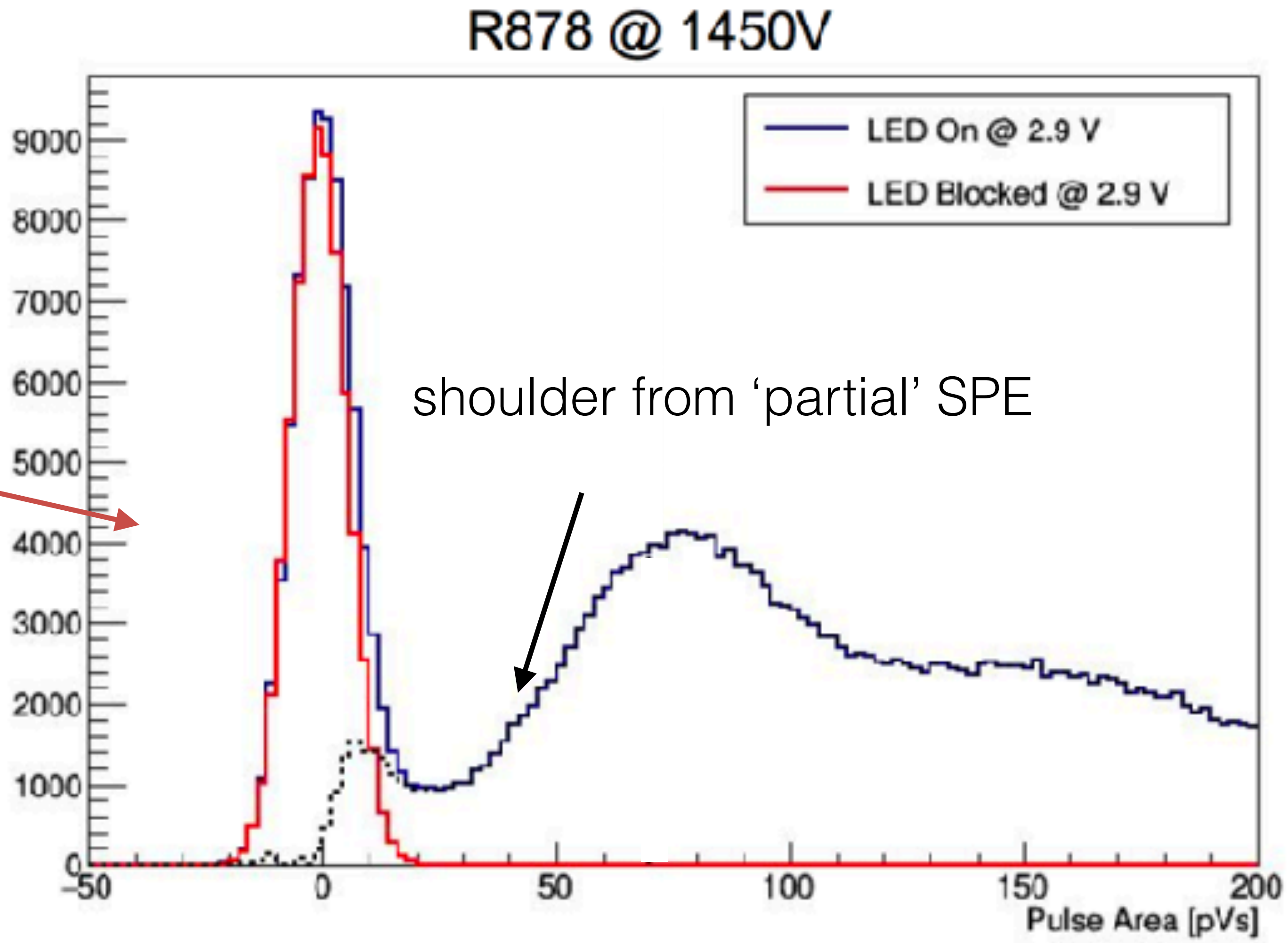
SPE calibration using LED

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)



shoulder from 'partial' SPE

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

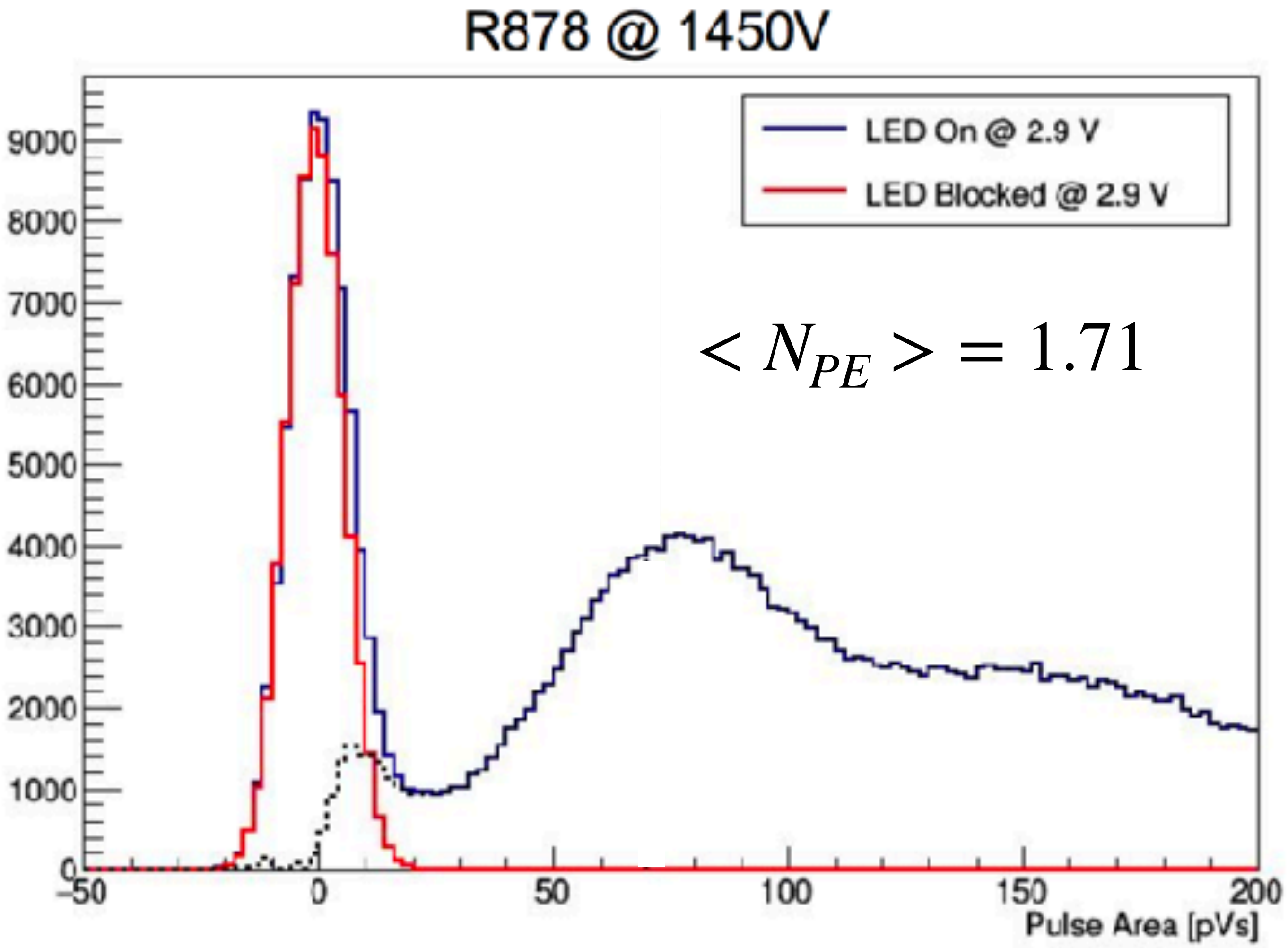
Now calculate SPE area

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!



$< N_{PE} > = 1.71$

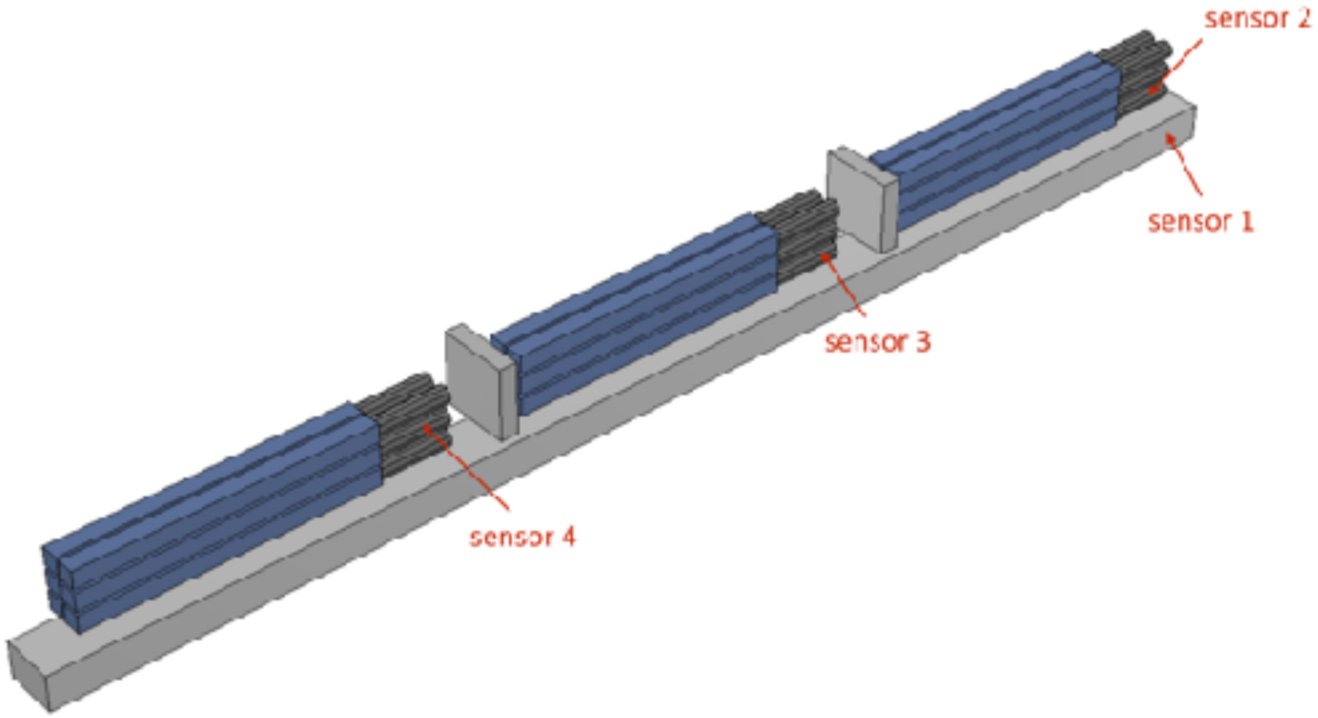
For this PMT (at 1450V):

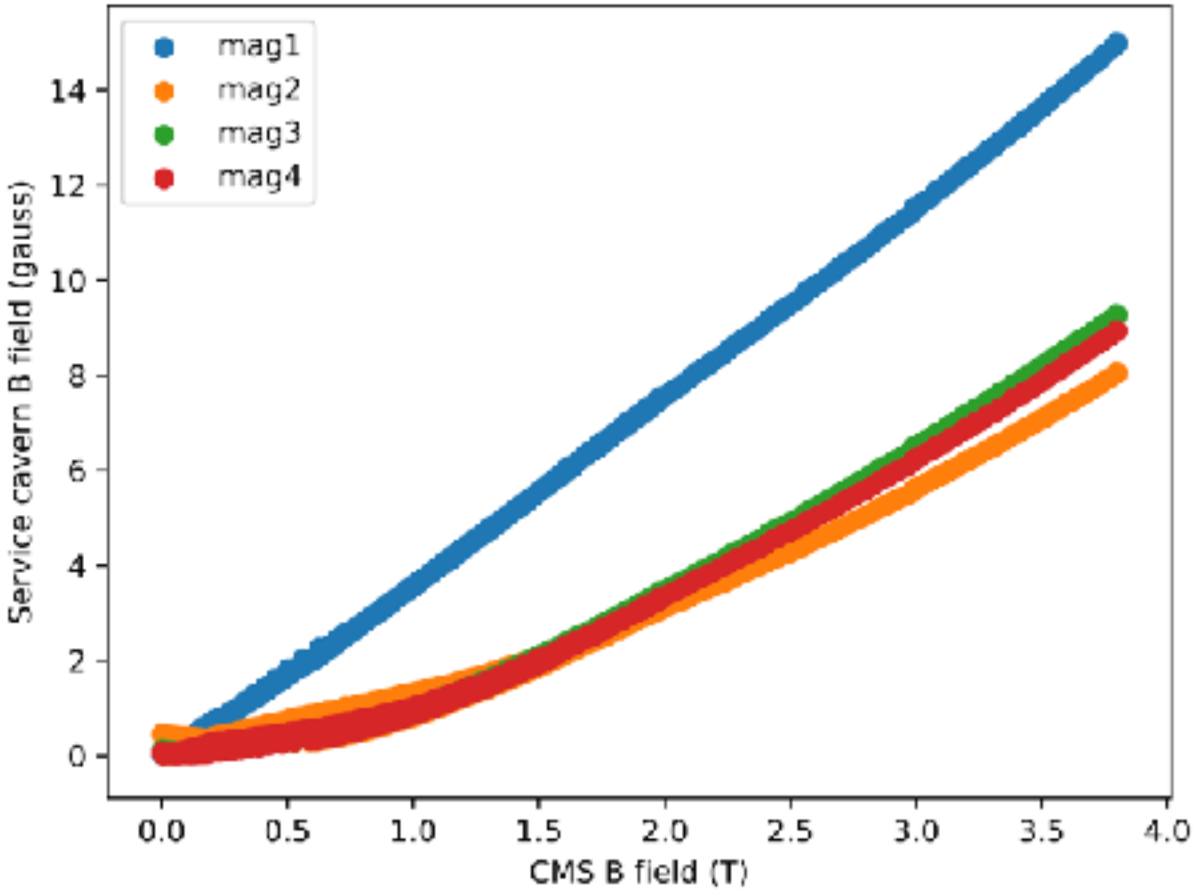
$$< A_{SPE} > = 69.9 \text{ pVs}$$

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

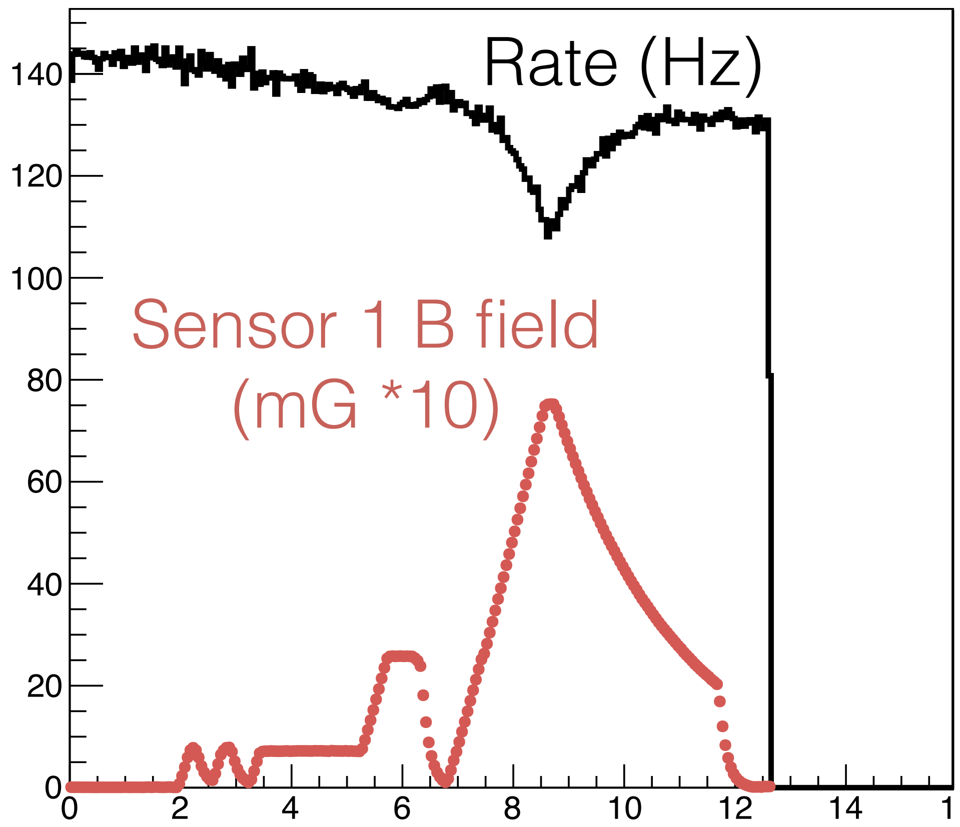
method from Saldanha et al., https://arxiv.org/abs/1602.03150

Effect of magnetic field



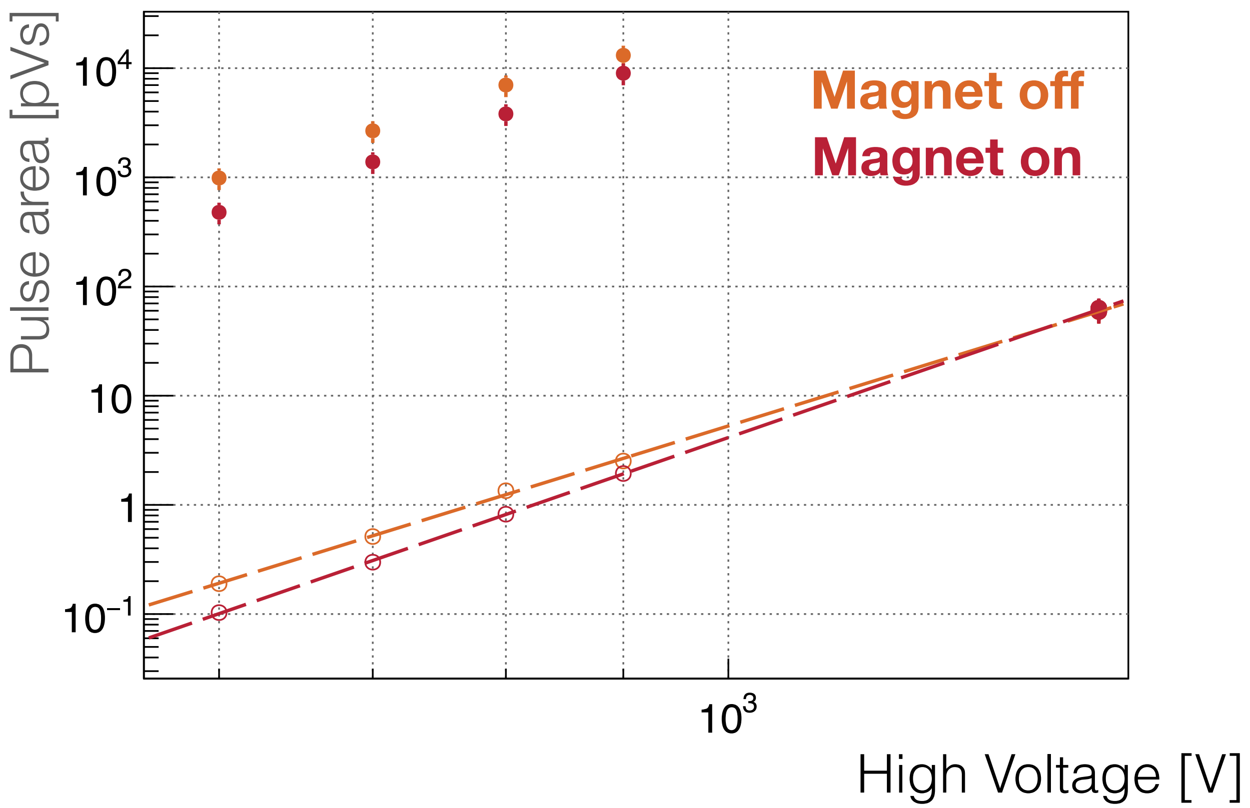


- Drainage gallery has residual magnetic field from CMS
- Measure field both inside and outside of PMT shielding (mu-metal)
- Look at effect on PMTs

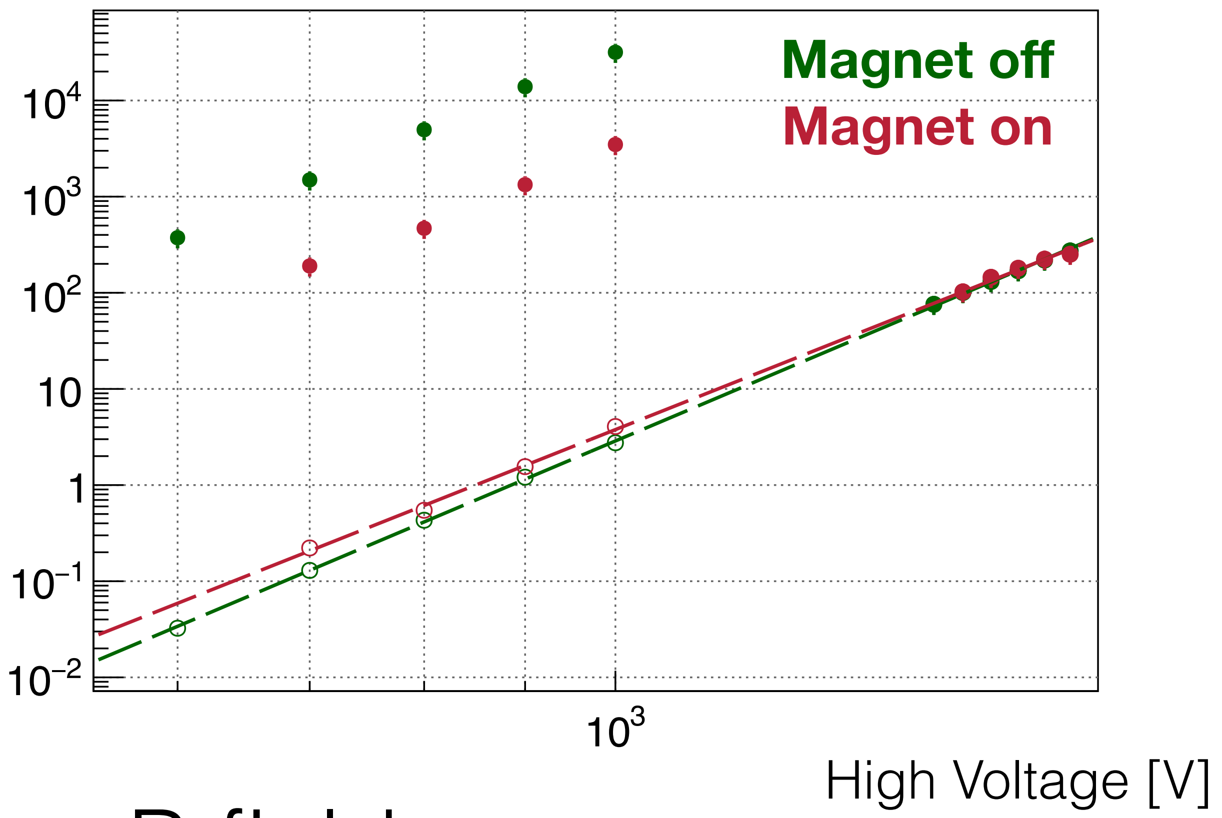


Effect of magnetic field

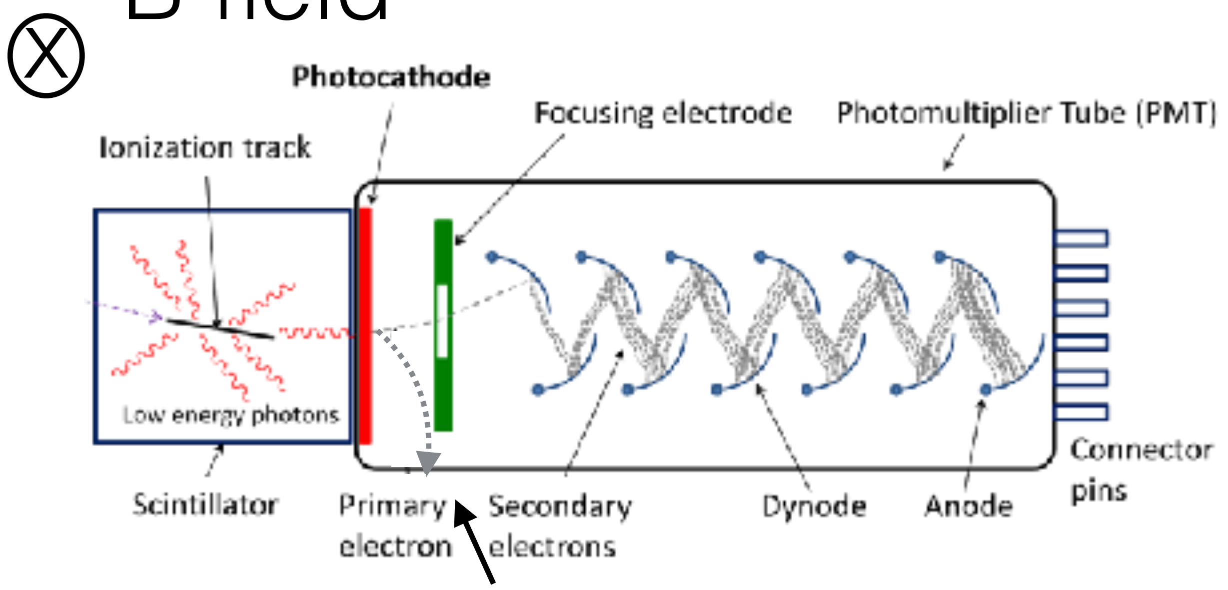
e.g. R878



e.g. R7725



B field



In B field can lose electrons!

- B field can have large effect on N_{PE} 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!)

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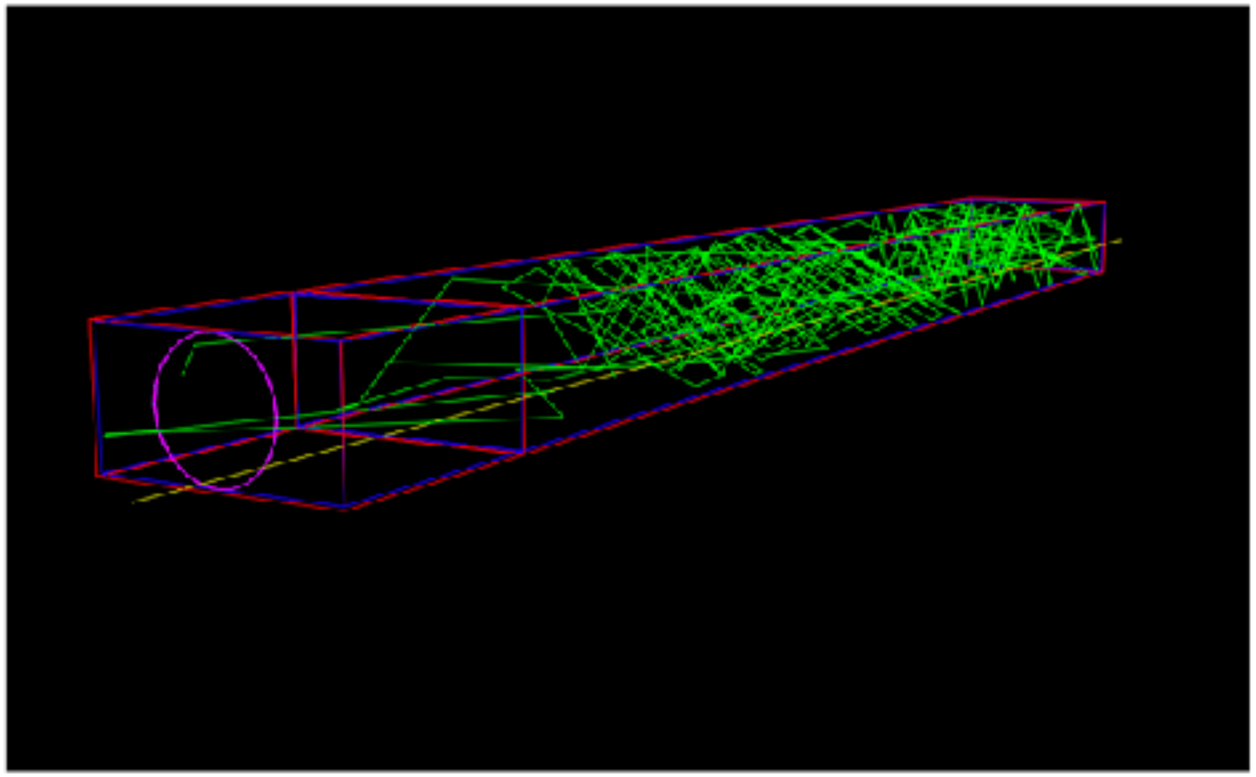
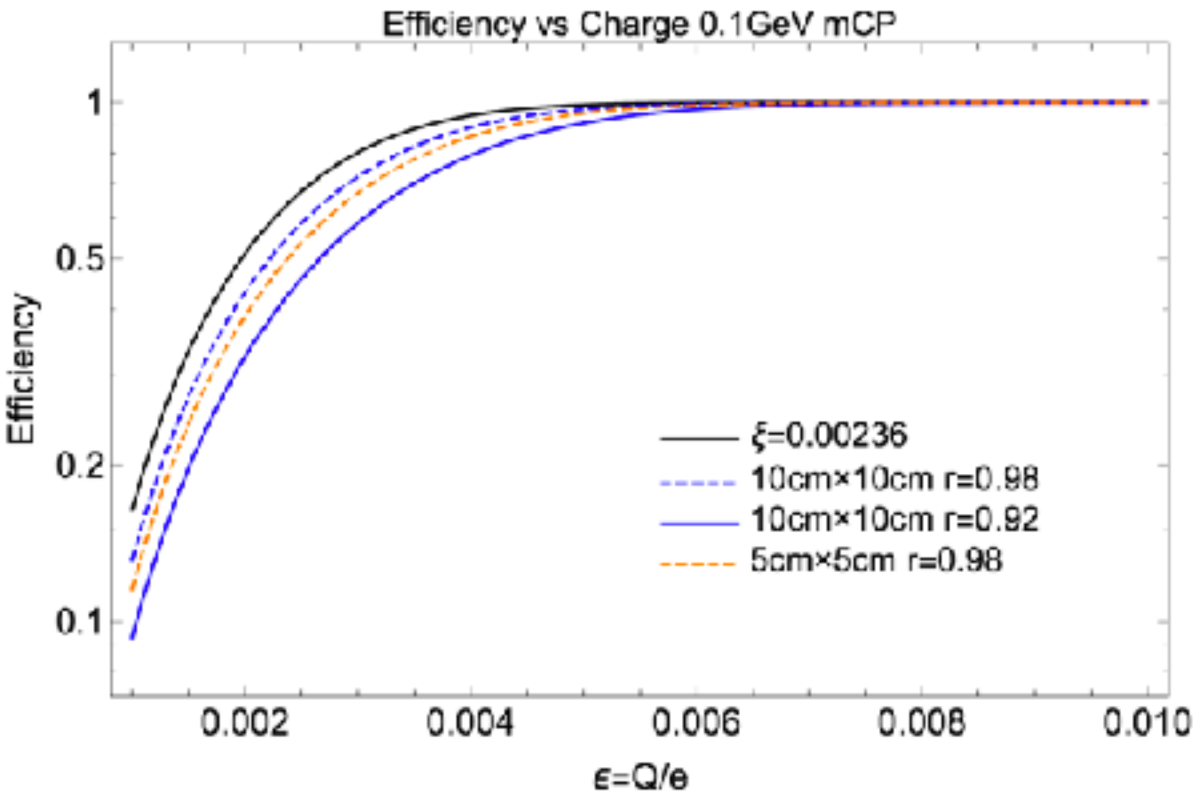
Detector simulation

- 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, …





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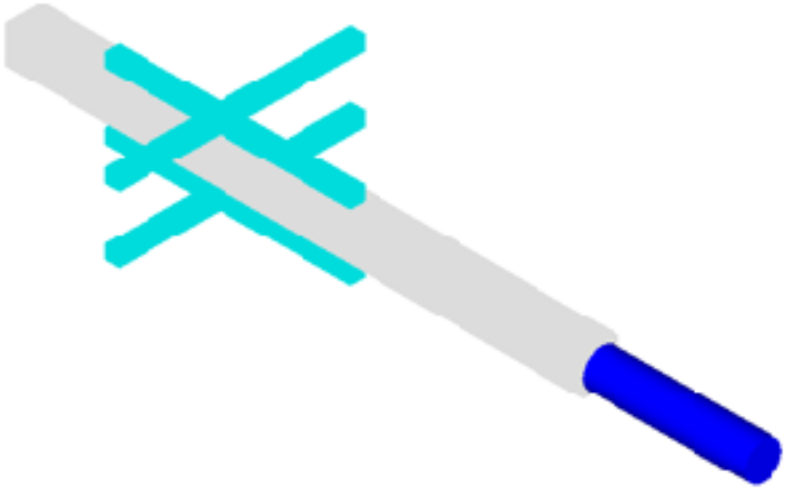
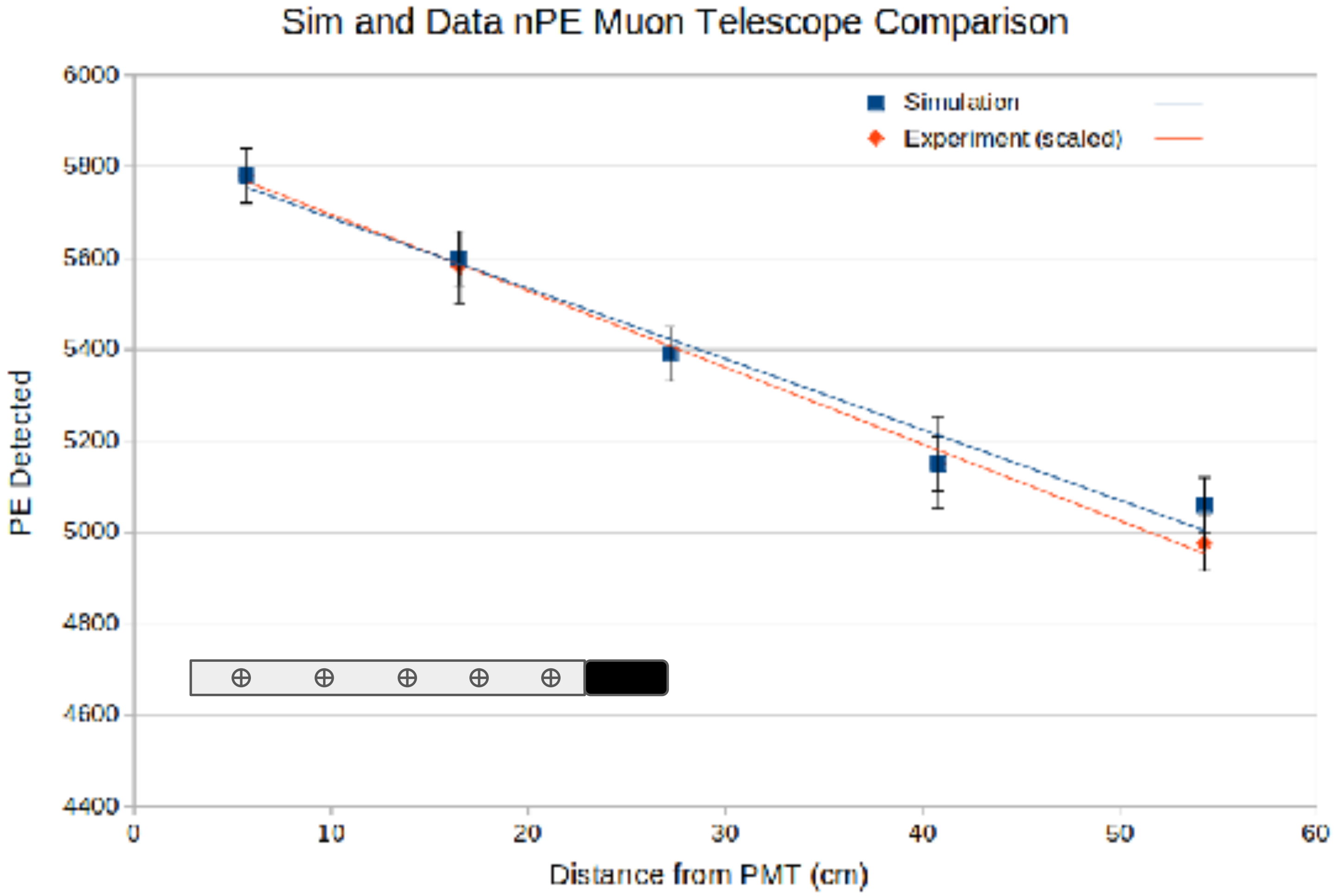
Calibrating detector simulation

- 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





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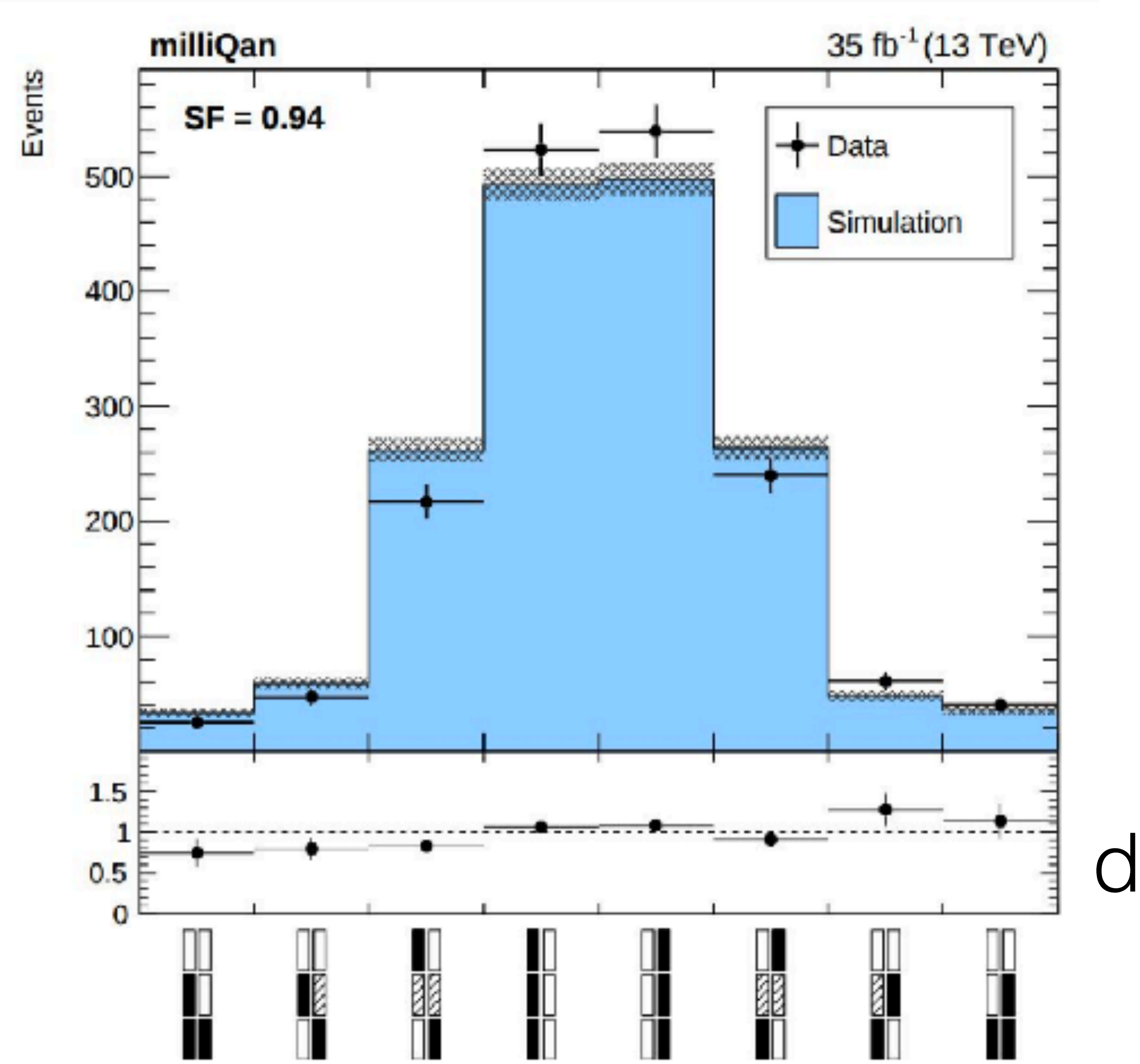
Validate angular description using paths through detector



Top view

Key

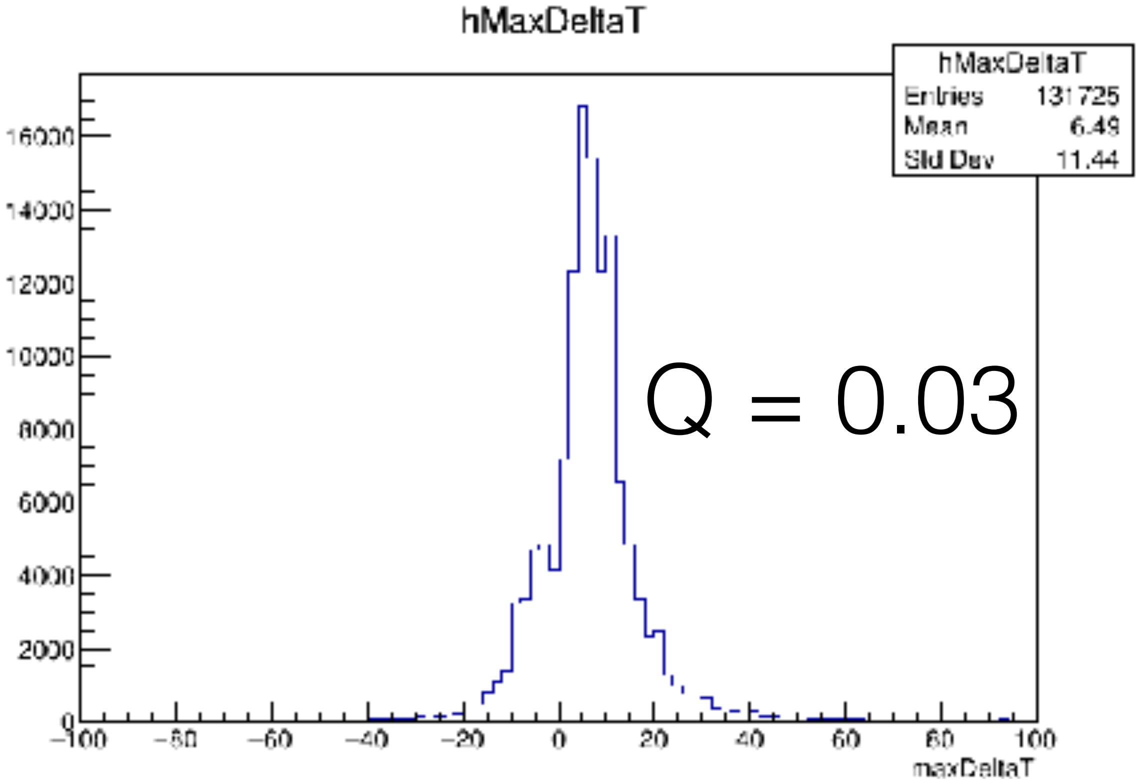
▯ = veto hit

▨ = allow hit

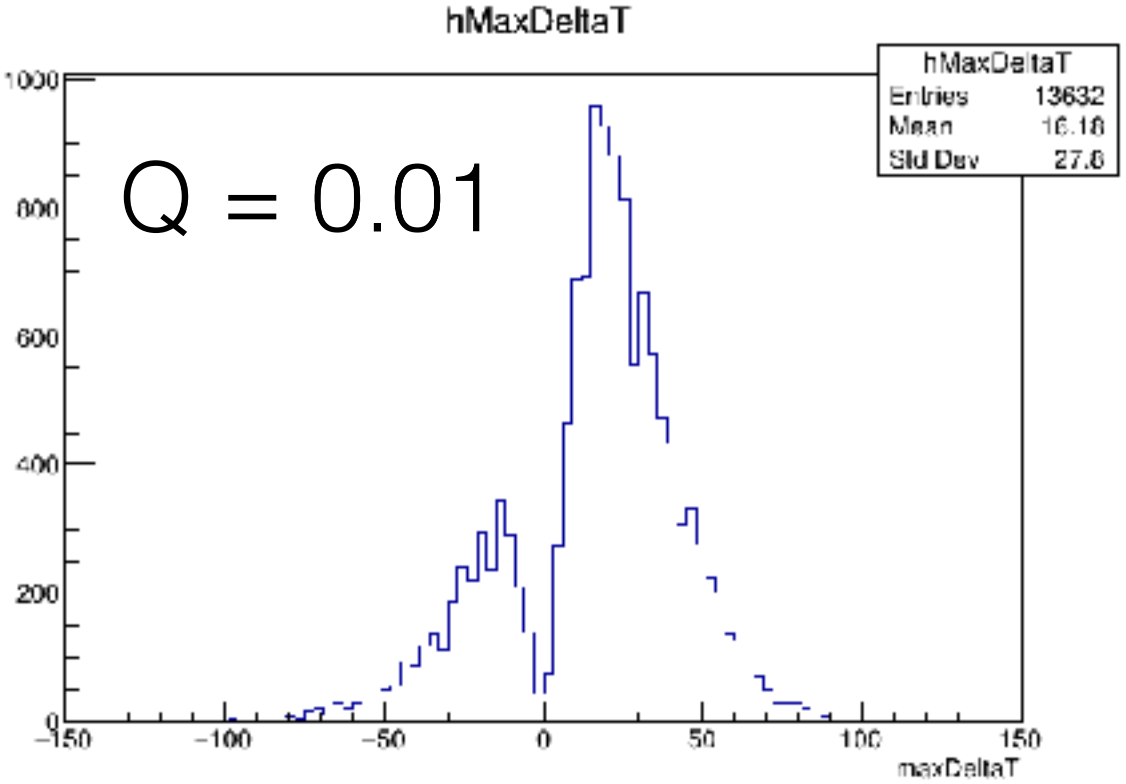
▮ = require hit

Angular spread through demonstrator well described by simulation!

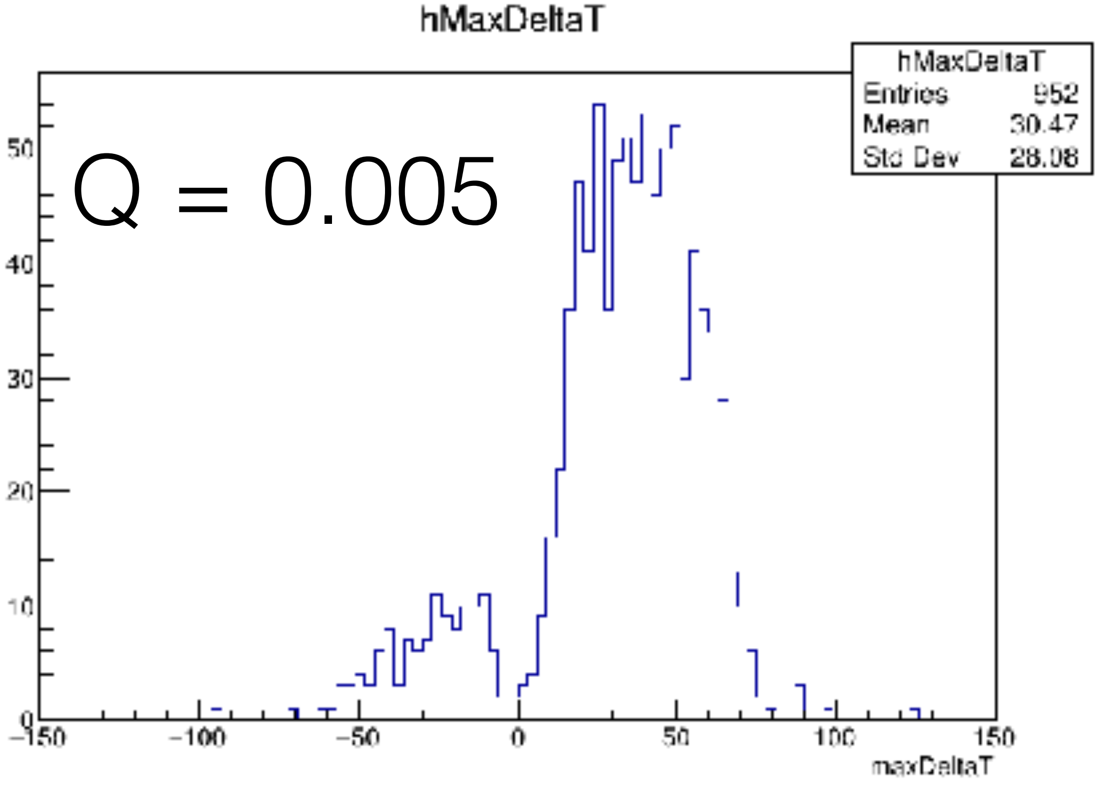
Timing for low charge (slab detector)



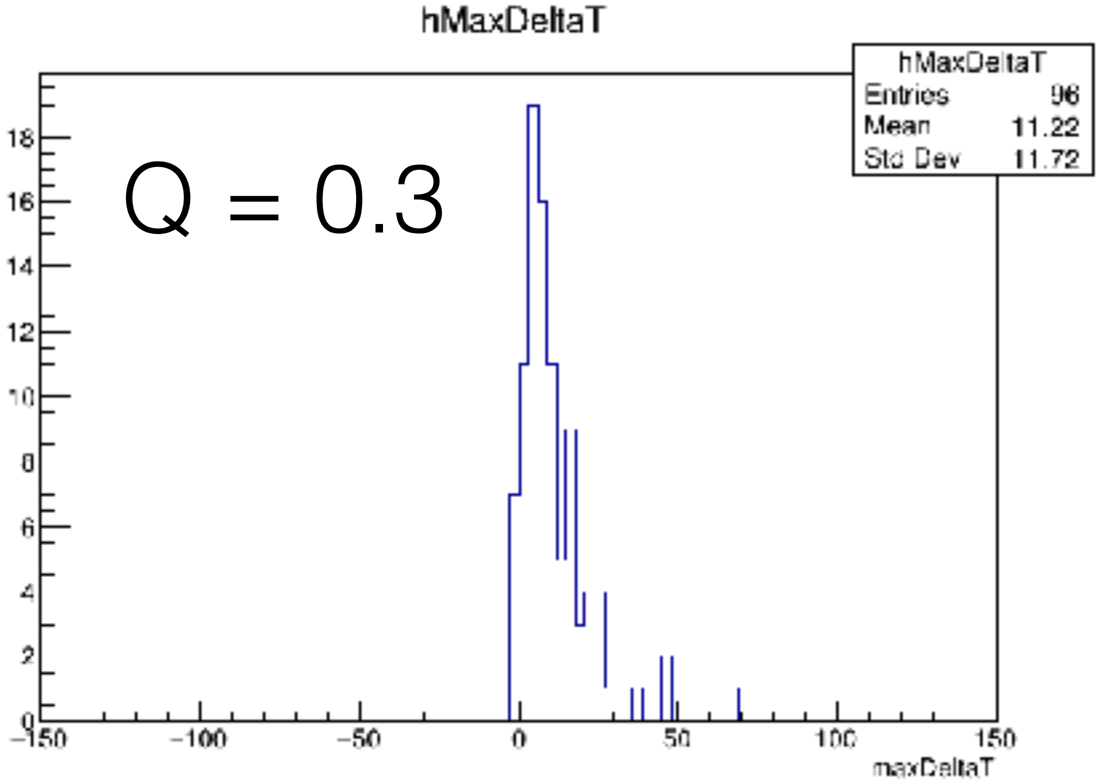
Q = 0.03



Q = 0.01



Q = 0.005



Q = 0.3

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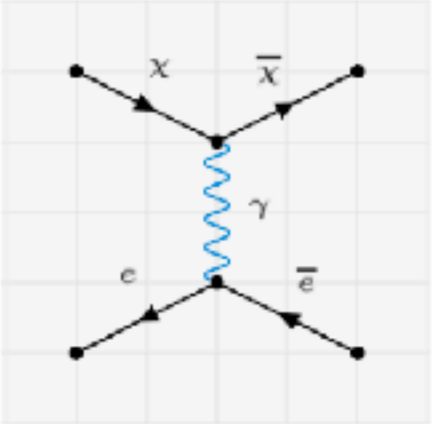
MCP Detection: Electron Scattering

- Q^2 is the squared 4-momentum transfer.
- lab frame: $Q^2 = 2m_e\,(E_e - m_e)$, $E_e - m_e$ is the electron recoil energy.
- Expressed in **recoil energy threshold,** $E_e^{(min)}$, we have

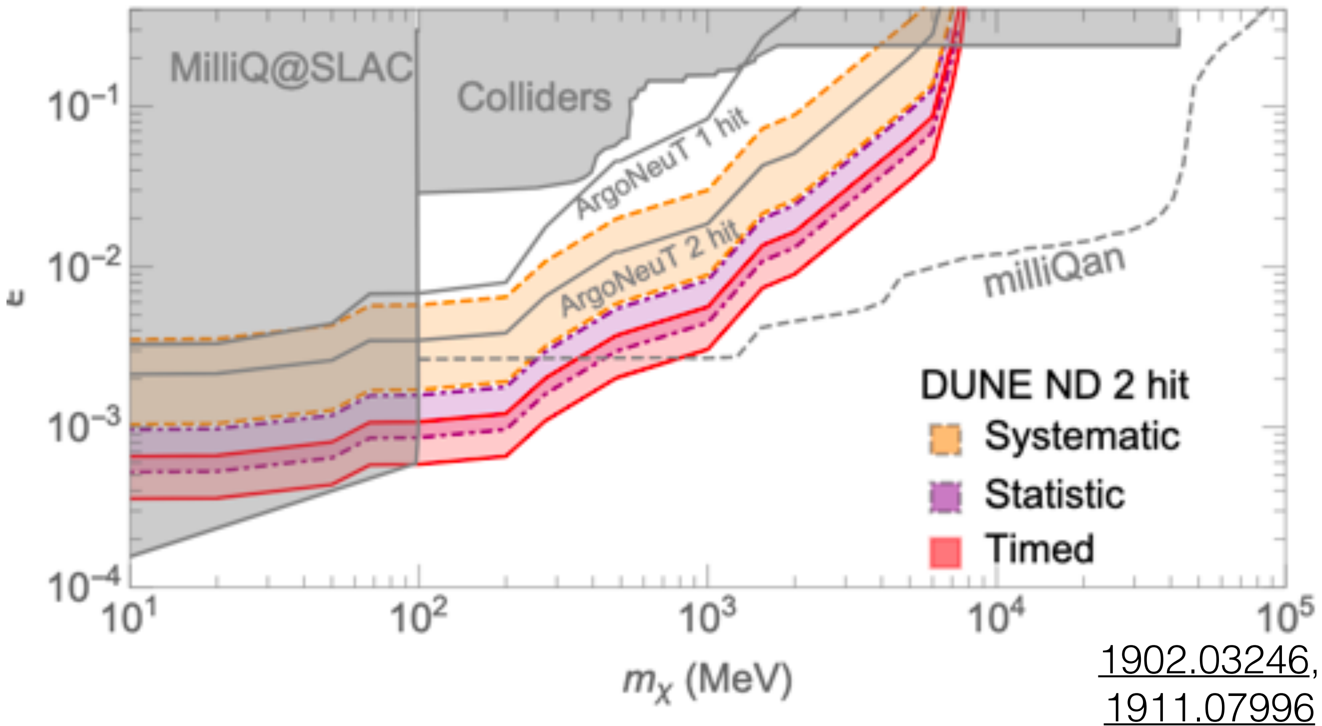
$$\sigma_{e\chi} \simeq 2.6 \times 10^{-25}\mathrm{cm}^2 \times \epsilon^2 \times \frac{1\ \mathrm{MeV}}{E_e^{(\mathrm{min})} - m_e}.$$

- Sensitivity greatly enhanced by accurately **measuring low energy electron recoils for MCP's & light-mediator scattering**



Yu-Dai Tsai

Searching for millicharge particles with neutrino detectors

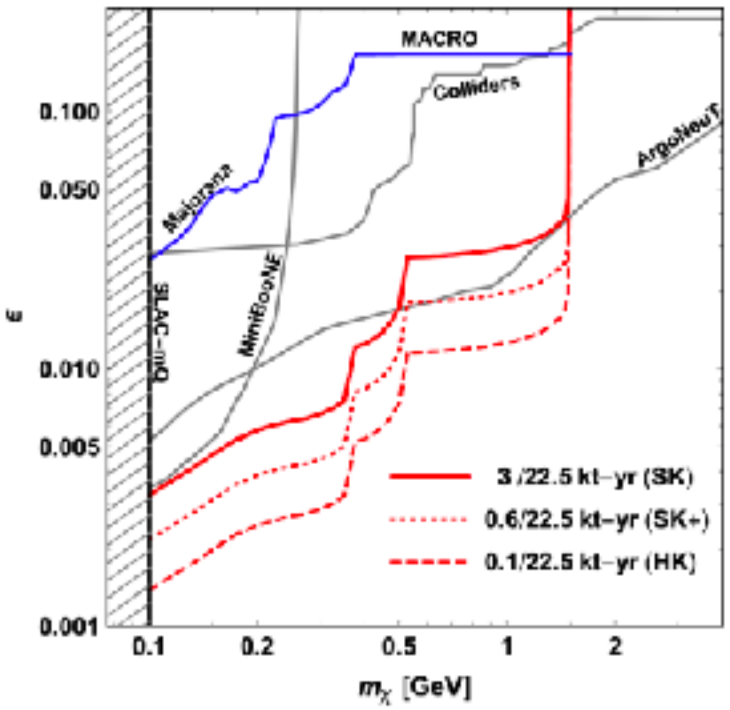


1902.03246, 1911.07996

Detection with LarTPC

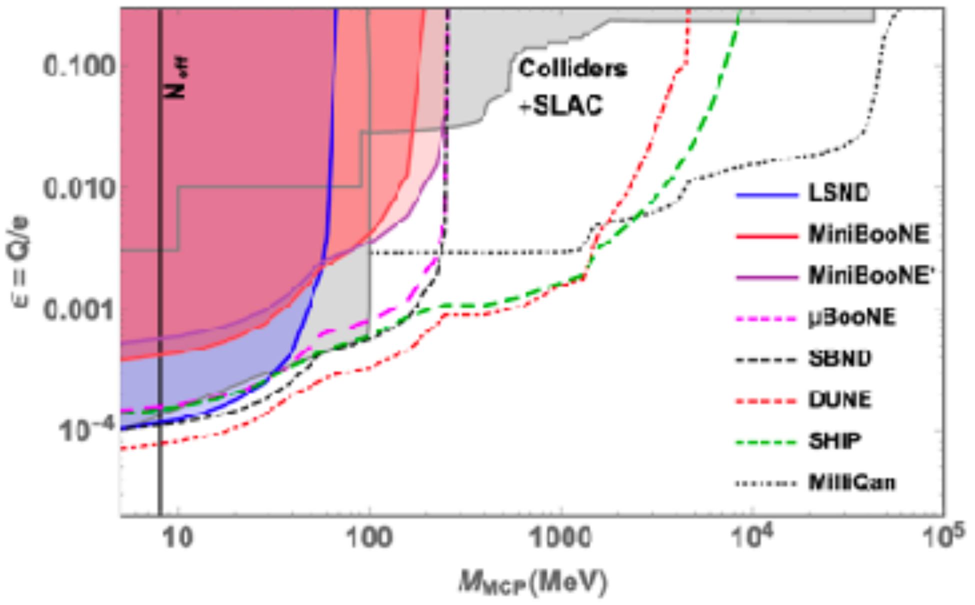
- Neutrino detectors provide sensitivity to millicharged particles through hard (> MeV recoil) electron scattering

- Many recent results and nice sensitivity prospects for DUNE



Production in cosmic ray showers

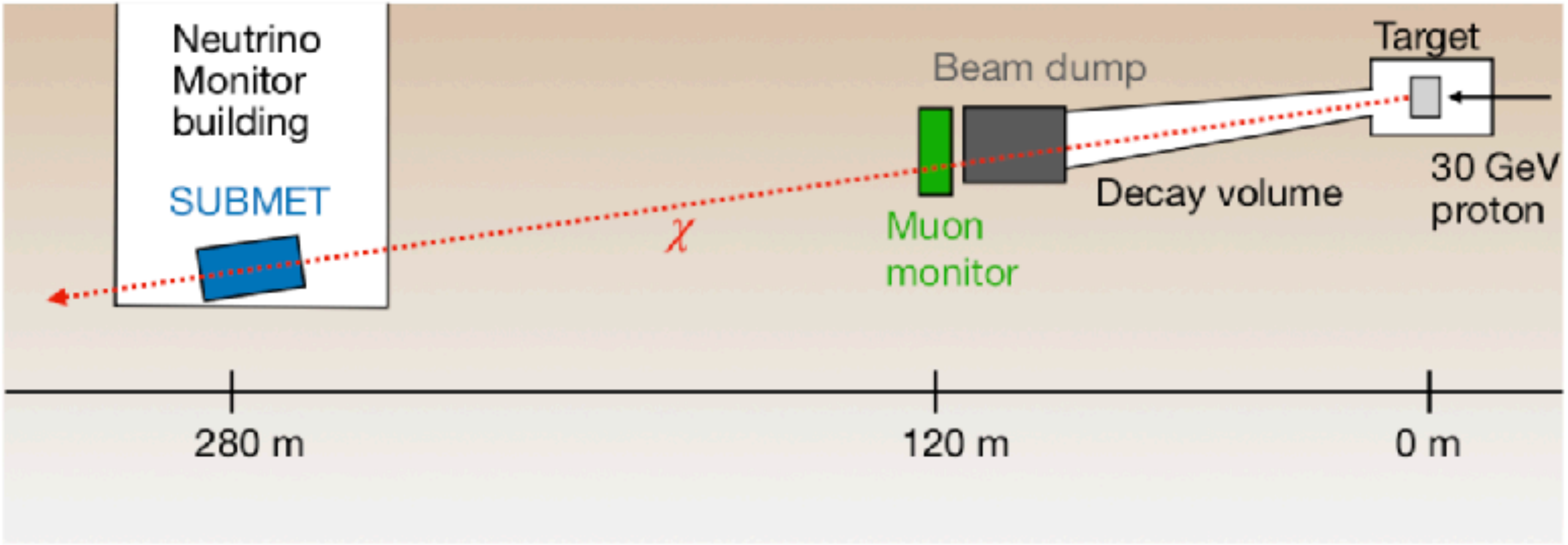
2002.11732



1806.03310

Fixed source neutrino experiments

SUBMET location



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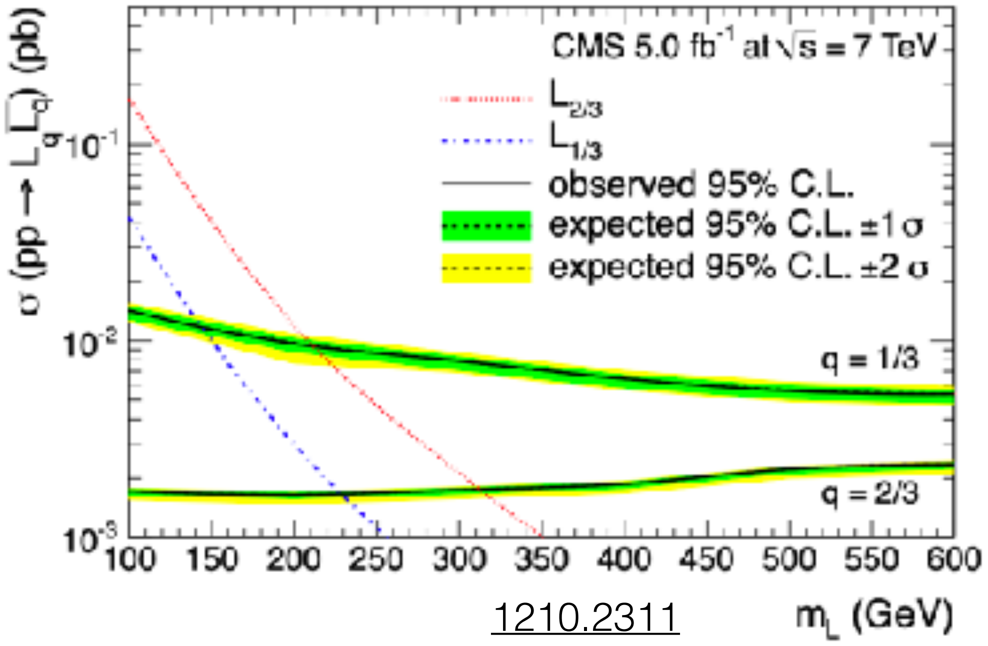
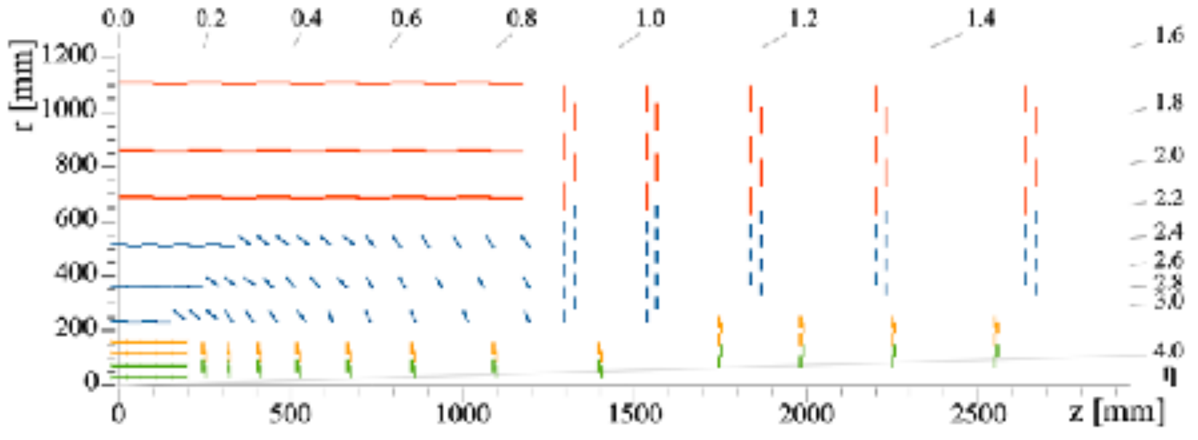
General purpose detectors at the LHC



1210.2311

Phase 2 tracker



Outer
tracker

- Much larger angular coverage than external detector provides sufficient acceptance for models up to O(100s) GeV but **sensitivity only for Q > 1/3 (FCPs)**

- Strategies: trigger on muons and look for low dE/dx hits in tracker (1210.2311, 1305.0491)

- In phase 2, CMS outer tracker only provides binary output

- Searches with dE/dX from (upgraded) muon system? Dedicated triggers? Dedicated low dE/dx readout bit? Timing measurement from MTD? Considerations for ATLAS/future detectors?

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