milliQan: A search for millicharged particles -- LHC Run 3 Plans

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on behalf of the milliQan collaboration

5/25/21, 9th LHC LLP Workshop

Paper: arXiv:2104.07151

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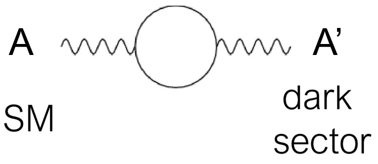
Why millicharged particles?

Standard motivation: Introduce new, hidden U(1) with a massless field A', a "dark photon" that couples to a massive "dark fermion" ψ'

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

massless "dark photon"

mixing term



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

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

- Ψ' has mass M_{mCP} and charge under the new U(1) of e'
- Gauge transformation of $A'_\mu \to A'_\mu + \kappa B_\mu$ introduces coupling $\overline{\psi'}\kappa e'\gamma^\mu B_\mu \psi'$
- **Conclusion:** Coupling arises between dark fermion and SM photon of charge $\kappa e' \cos\theta_W$. mCP parameters are **entirely defined by their mass and charge**

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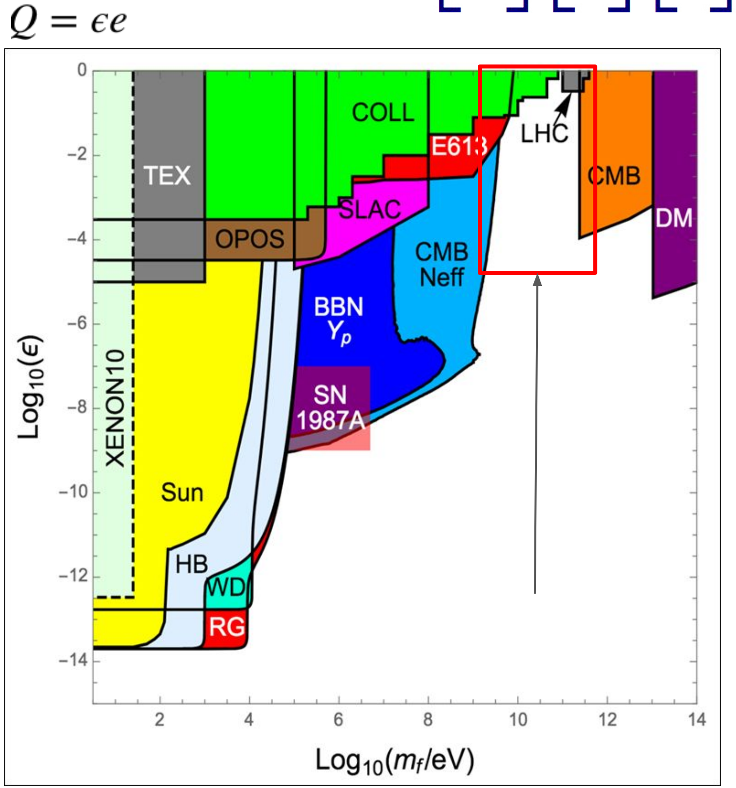
State of mCP phase space

Direct constraints (collider + beam dump experiments) and indirect constraints (solar effects, supernovae, cosmological bounds) cover a wide range of masses/charges

BUT

There seems to be a natural, unexplored region for ~GeV masses, especially at low charge. These evade general-purpose LHC detectors since dE/dx ~ Q^2

milliQan targets this phase space. What does that look like? Let's look at the **milliQan demonstrator.**



arXiv:1511.01122

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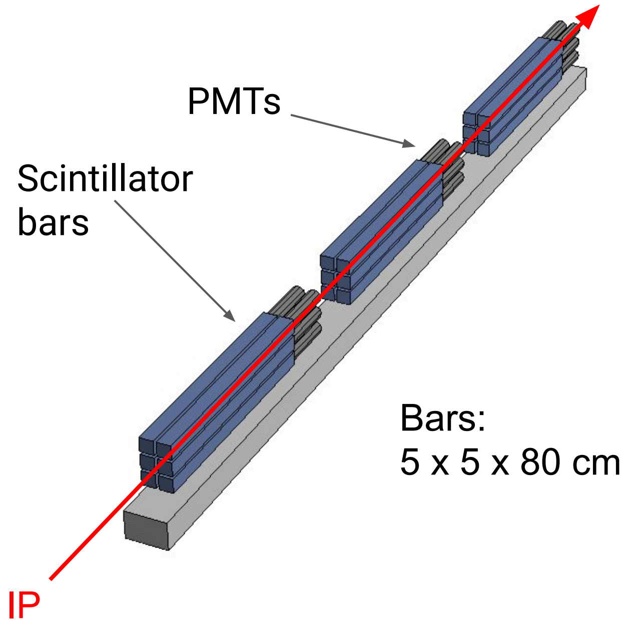
milliQan demonstrator overview

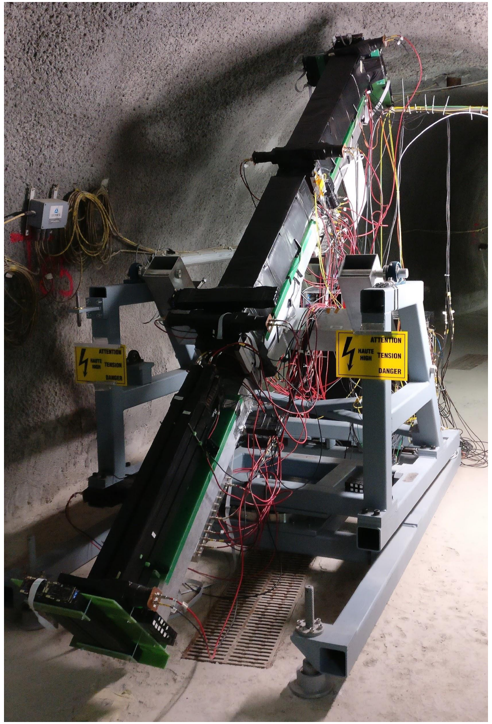
Proof of concept: We constructed a ~1% prototype of the full milliQan detector design: the **milliQan demonstrator**

Demonstrator is built from:

- 3x2 Scintillator + PMTs



Bars:
5 x 5 x 80 cm



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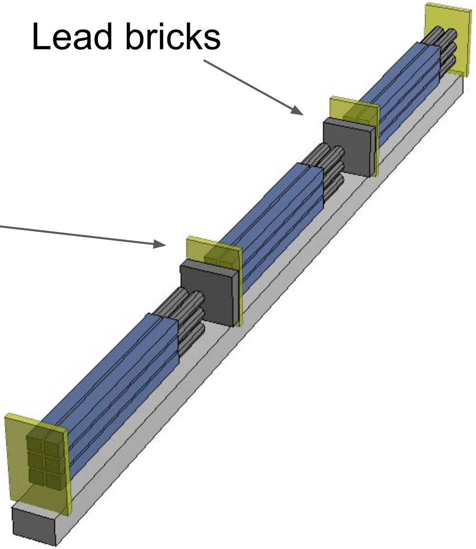

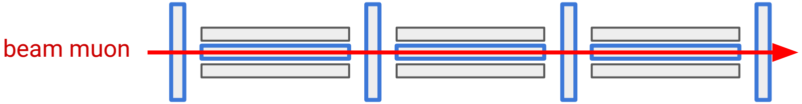

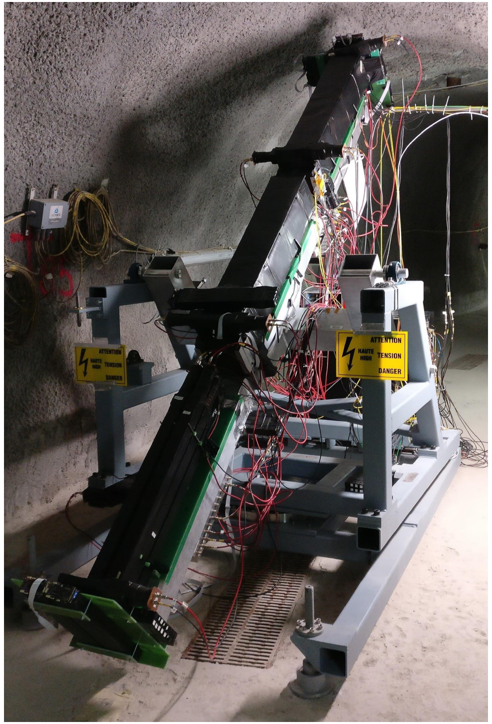

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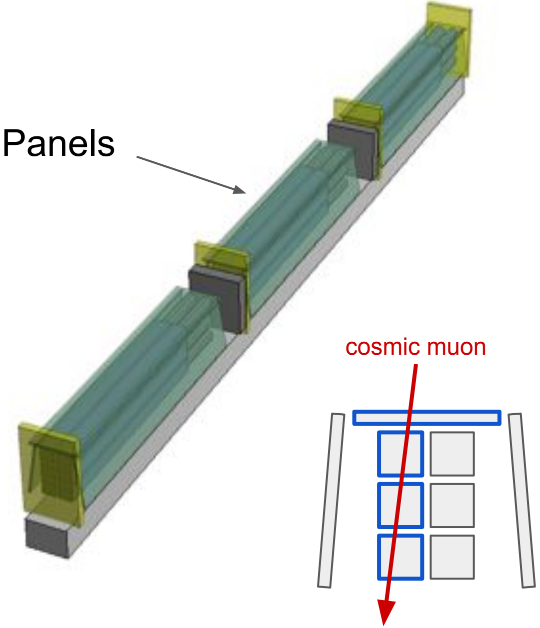

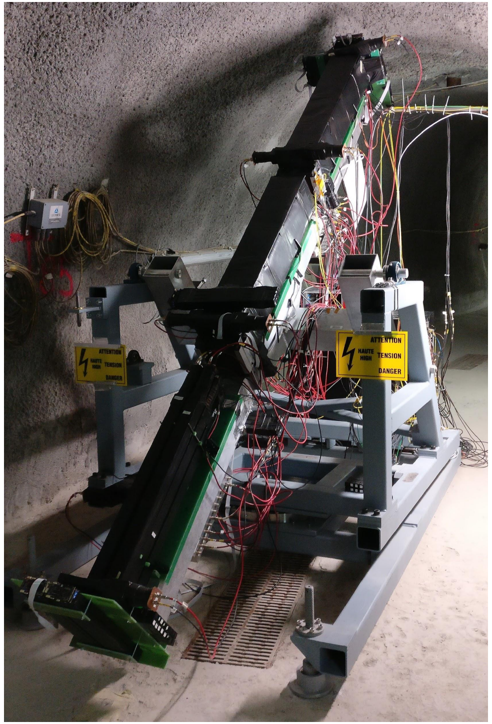

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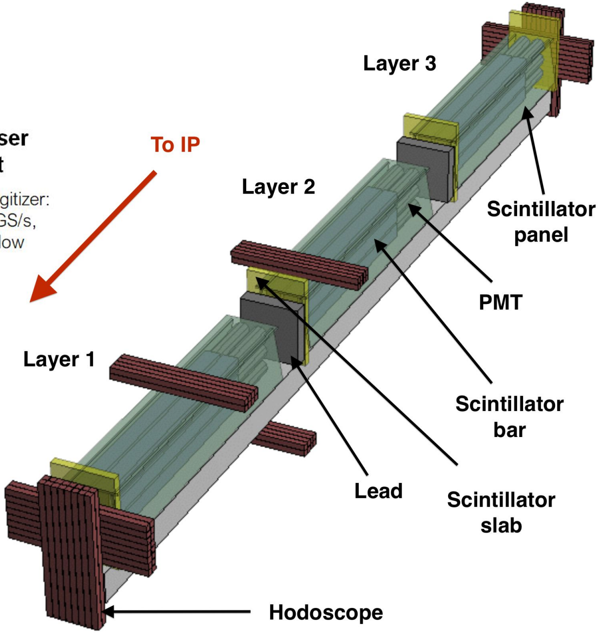
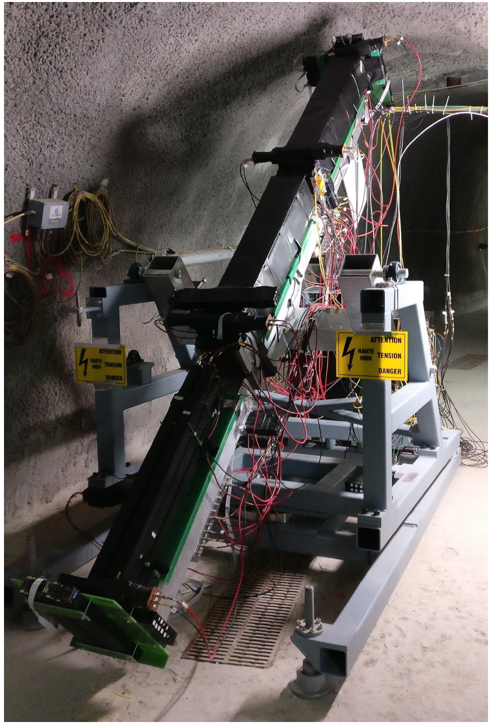
- 3x2 Scintillator + PMTs
- Scint + Pb slabs between layers, veto throughgoing background, radiation
- Scint panels surrounding each layer, identify cosmic muons
- All channels read out with high speed digitizer to enable triggering
  - Self trigger on 3 channels above 1 PE

dual digitiser readout

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





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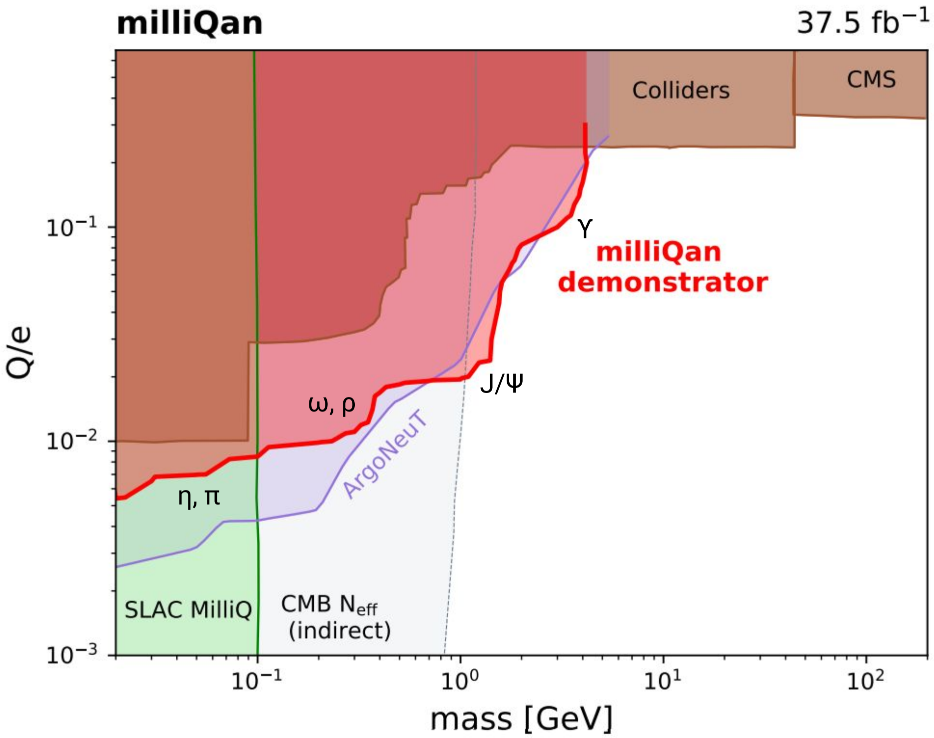
milliQan demonstrator sensitivity

The milliQan demonstrator achieved competitive constraints on mCPs between masses M ∈ [20, 4700 MeV] and charges Q/e ∈ [0.006, 0.3]

The demonstrator provided new exclusion limits, but also strong, quantitative understanding of milliQan backgrounds and detector performance

→ Use this to guide designs for Run 3 and beyond! Let's take a look at the lessons learned



PhysRevD.102.032002

Run 3 milliQan bar detector design

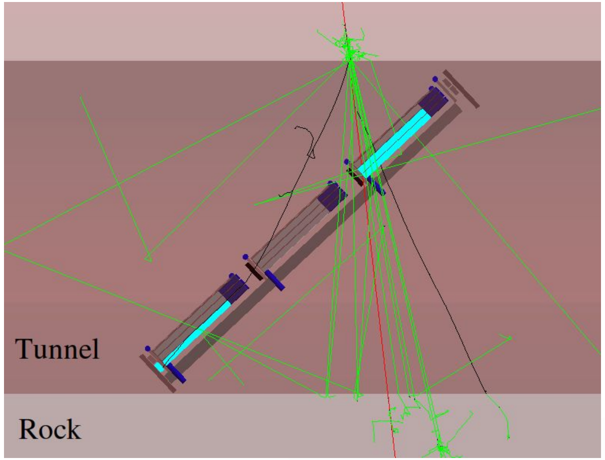
- **Important lesson:** Cosmic muon shower secondaries form a significant background. **Four layers of scintillator bars are needed** to control background from cosmic ray showers

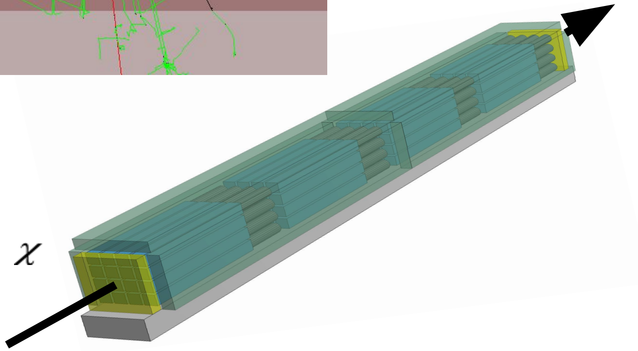
- **Expanded size of each layer** (2x3 --> 4x4 scintillator bars) to improve background rejection and increase signal acceptance. **Self shielding** becomes important the larger the detector becomes

- **Increased thickness of scintillator veto “panels/slab”** to 5cm for improved shower tagging

- **Dedicated signal amplification** to improve reconstruction of very low energy deposits. Means we can reuse PMTs, minimize cost!

- Make use of LED “flashers” and radioactive sources to **improve response and timing calibrations**





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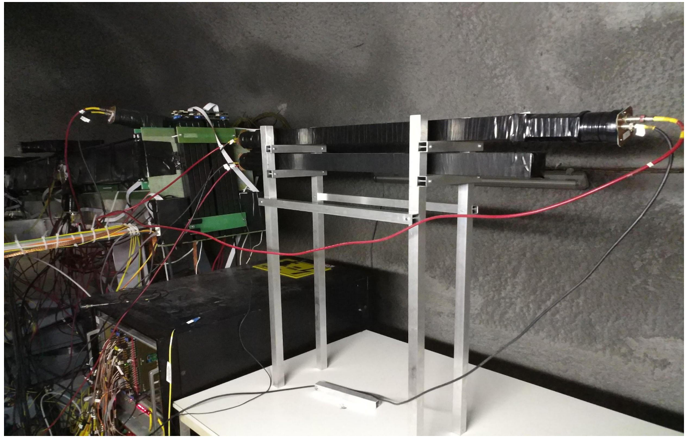
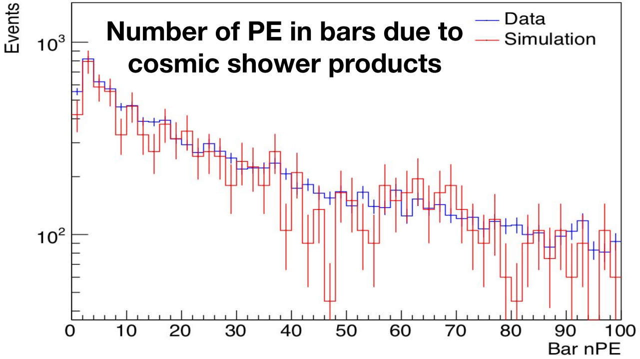
Cosmic background characterization

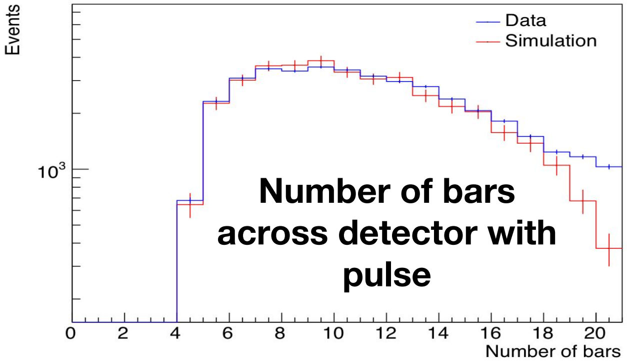
How are cosmic backgrounds estimated? A key facet of Run 3 and beyond detector design: **GEANT4 simulation**

- Cosmic and beam muons first propagated through surrounding rock, then simulated explicitly in GEANT
- Crucial variables are compared between simulation and a “four layer demonstrator” used for validation
- Data of the cosmic shower background shows **good agreement with simulation**

Therefore: Use simulation to estimate Run 3 cosmic backgrounds







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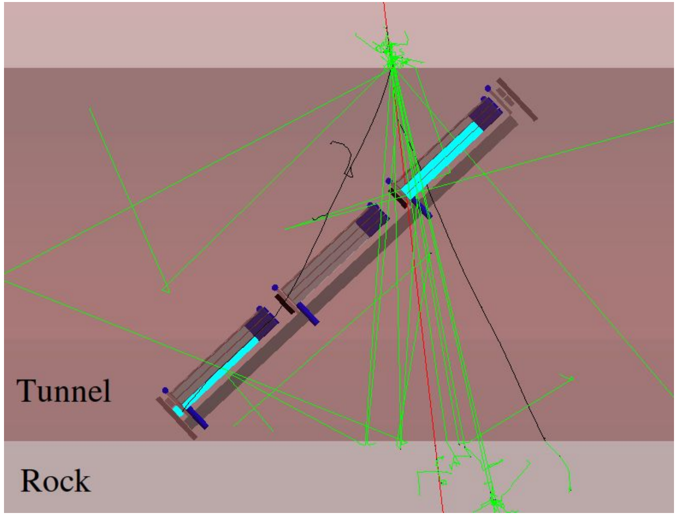
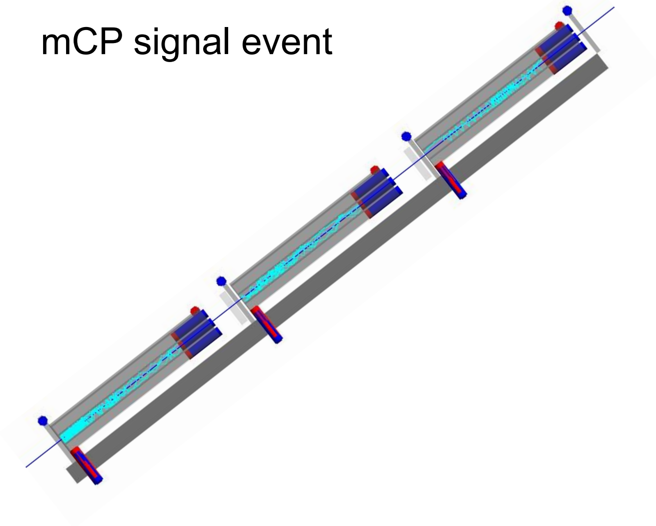
Signal Selection: Key Features

Cosmic shower background event



mCP signal event



Key features of milliQan signal selections:

Exactly one bar hit per layer, in a line pointing towards the IP

Vetoing on muons + high energy background

Energy deposits consistent with a mCP

Detection timing consistent with a mCP originating from the IP

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Background Prediction

Backgrounds were evaluated using this GEANT4 simulation, calibrated and validated against the four layer demonstrator, using selections motivated by the Run 2 demonstrator search

Together, these requirements reject backgrounds while maximizing signal efficiency

Key features of milliQan signal selections:

Exactly one bar hit per layer, in a line pointing towards the IP

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Energy deposits consistent with a mCP

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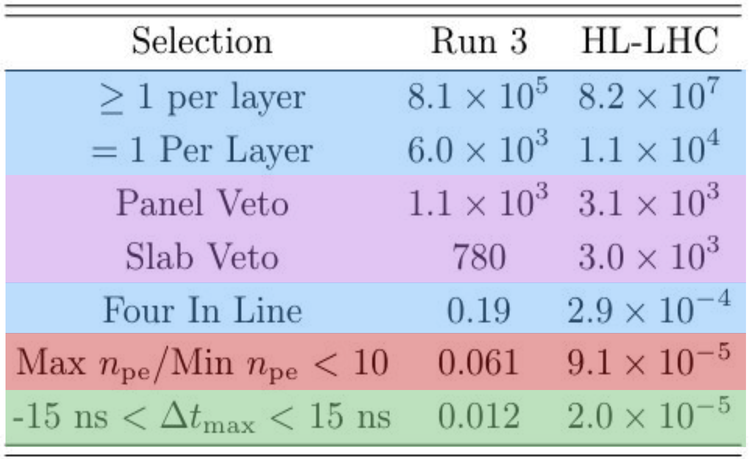
Cosmic Backgrounds



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 $< \Delta t_{\max} <$ 15 ns	0.012	2.0×10^{-5}
Dark Rate	0.05	1.4

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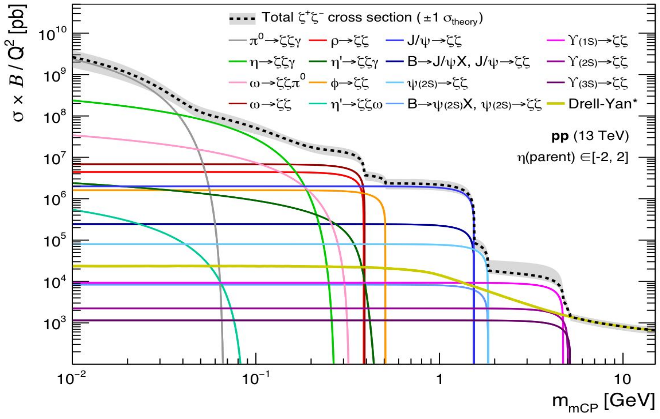
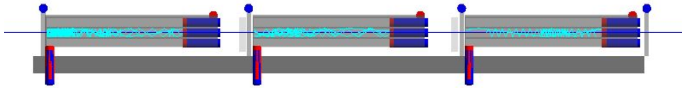
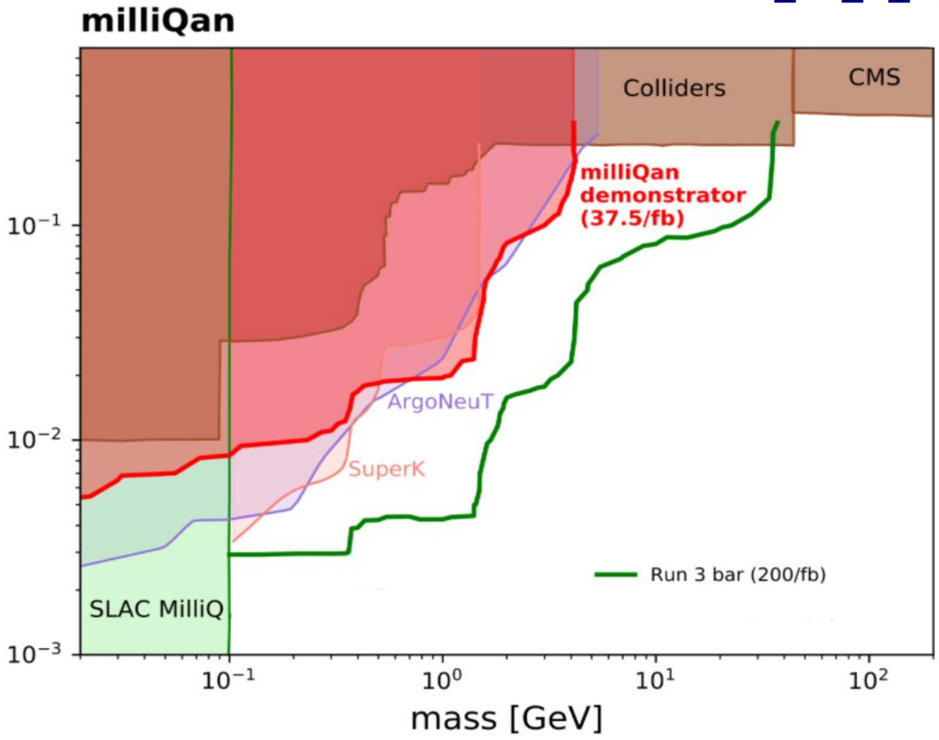
Projections

Signals were generated over a broad set of production modes, then passed through the calibrated GEANT4 simulation







What happens if we add more bars? We increase acceptance without sacrificing charge sensitivity. What does that look like?

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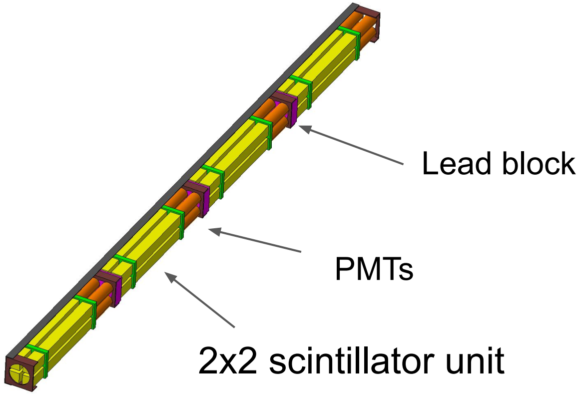
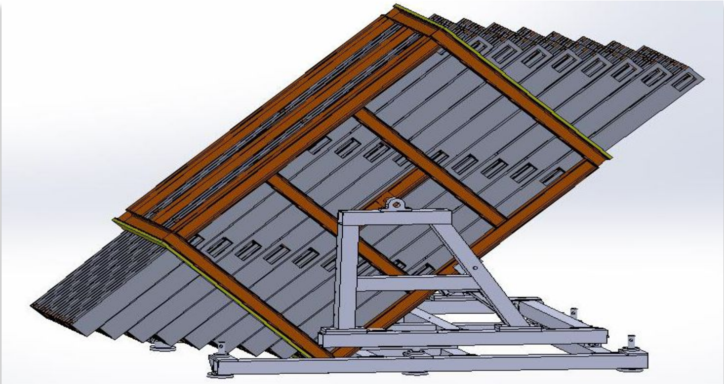
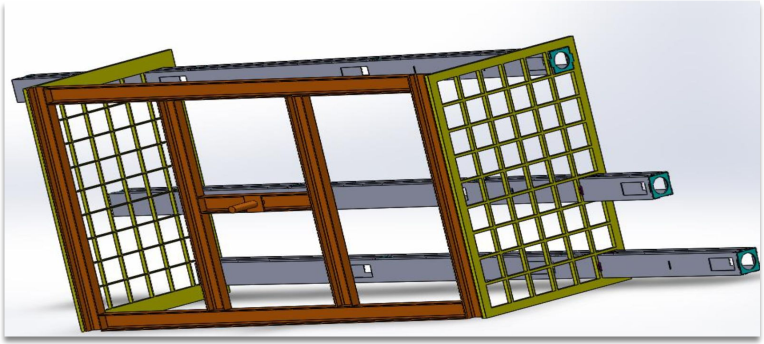
HL-LHC milliQan bar detector design

Beyond Run 3, we plan to expand the milliQan design to fill the entirety of the available space:

9 units x 6 units x (2x2 bars per unit) x 4 layer = 864 bars (1 x 1 x 3 m)







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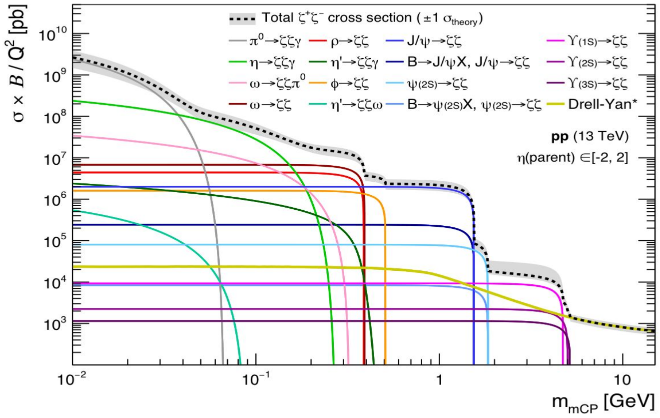

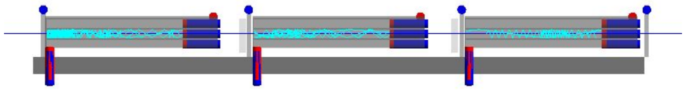

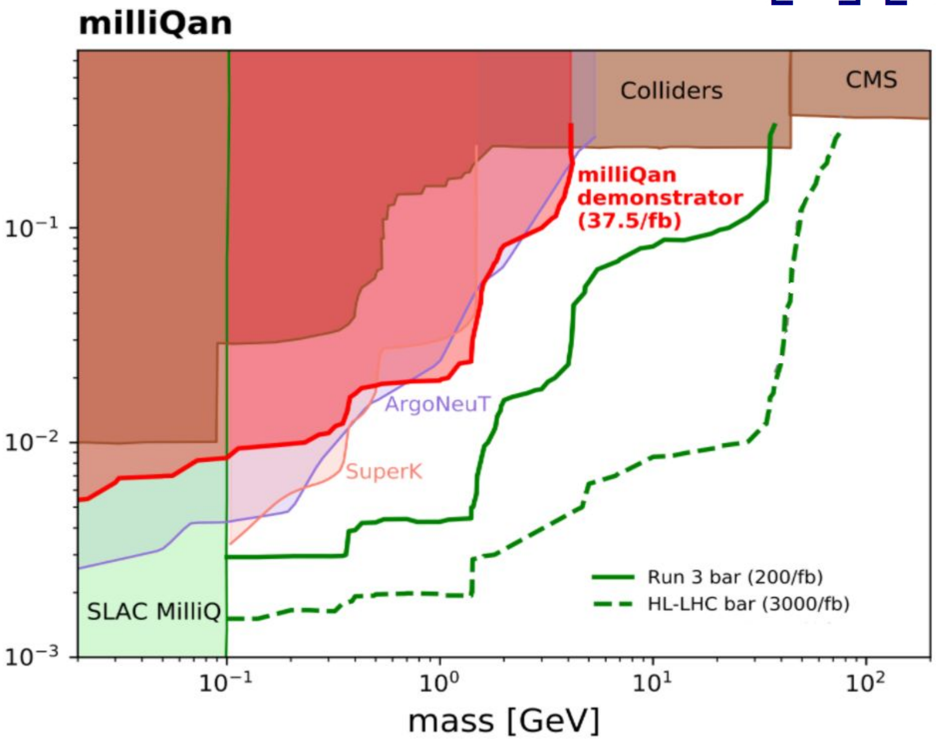

Projections show **Run 3 detector will significantly expand reach,** and the **HL-LHC design does even better**

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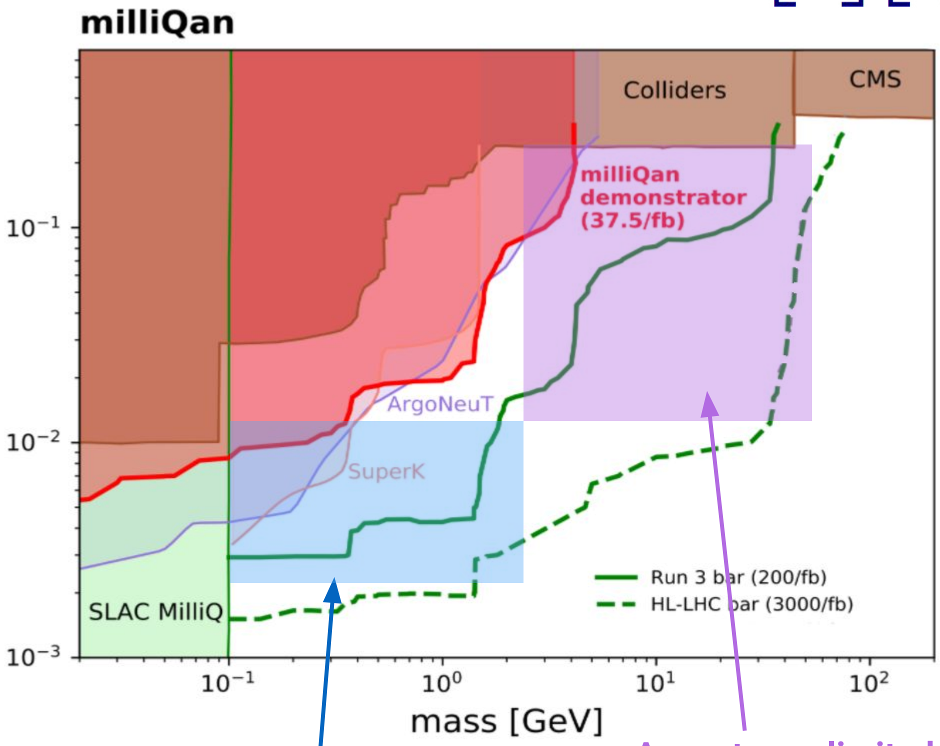
Optimizing Detector Design

With the Run 3 detector funded, we can explore other design ideas that exploit the advantages of milliQan

Much of the phase space where milliQan drives sensitivity is in the high mass region-- where sensitivity is **acceptance-limited** rather than charge-limited

Solution: Use scintillator slabs, not bars, to maximize acceptance!



Charge limited region: very high mcp flux but low efficiency

Acceptance limited region: high efficiency but mcp flux is low

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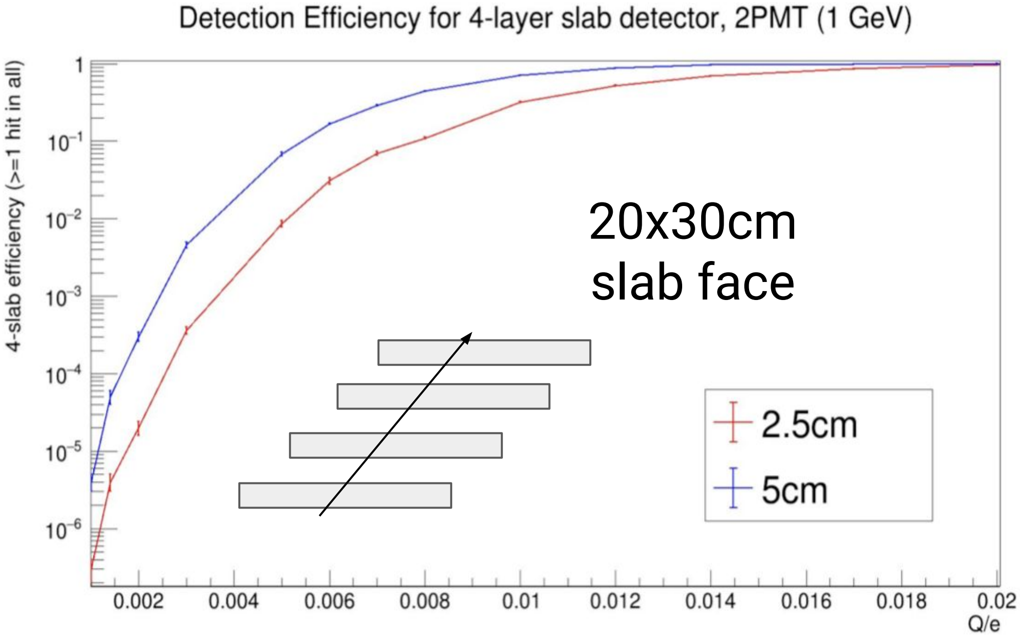
milliQan slab detector sensitivity

We can estimate slab charge sensitivity by using GEANT to determine the probability that >=1 photon is detected in all 4 layers of a slab detector

A 5cm-thick slab will be sensitive down to Q=0.01-- much thicker gives diminishing returns

So, we introduce a new idea:
The milliQan slab detector, a separate detector installed alongside the bar detector to target acceptance-limited regions of phase space



20x30cm slab face

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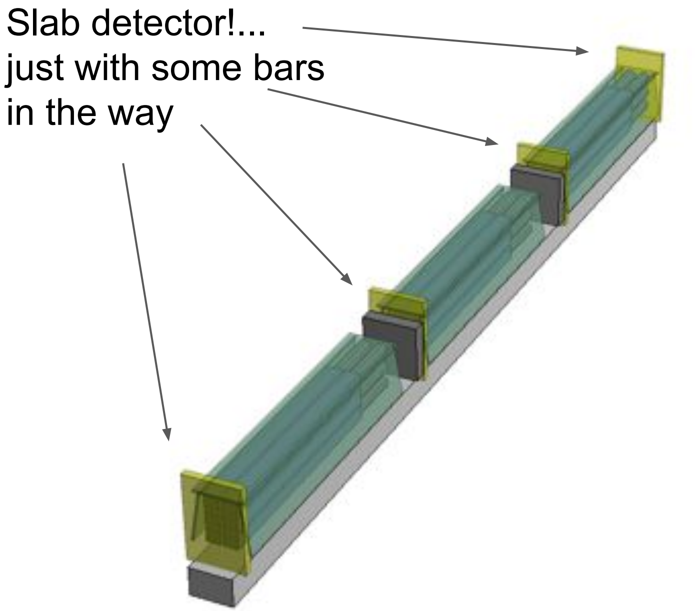
Slab Background: Demonstrator

Our demonstrator was a sort of 4-layer slab detector: one with bars in between layers of slabs

These bars will only increase cosmic shower backgrounds seen in the slab-only demonstrator

If the backgrounds are reasonable, then, the slab detector concept is viable. Are they?



Slab detector!... just with some bars in the way

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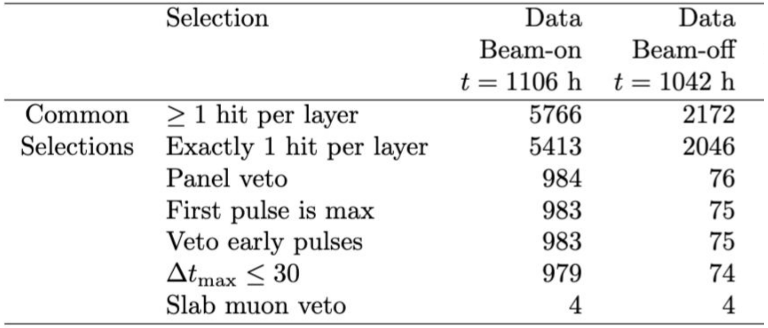
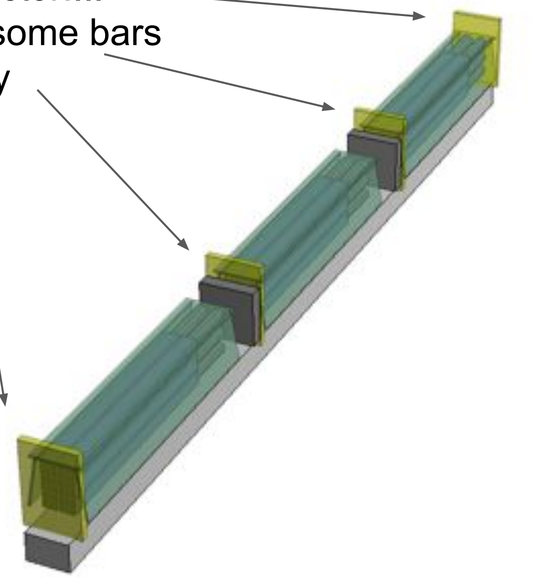


	Selection	Data Beam-on $t = 1106$ h	Data Beam-off $t = 1042$ h
Common Selections	≥ 1 hit per layer	5766	2172
	Exactly 1 hit per layer	5413	2046
	Panel veto	984	76
	First pulse is max	983	75
	Veto early pulses	983	75
	$\Delta t_{\max} \leq 30$	979	74
	Slab muon veto	4	4

Slab detector!...
just with some bars
in the way



YES. Bars effectively not necessary to reject background. **So a slab detector can work!**

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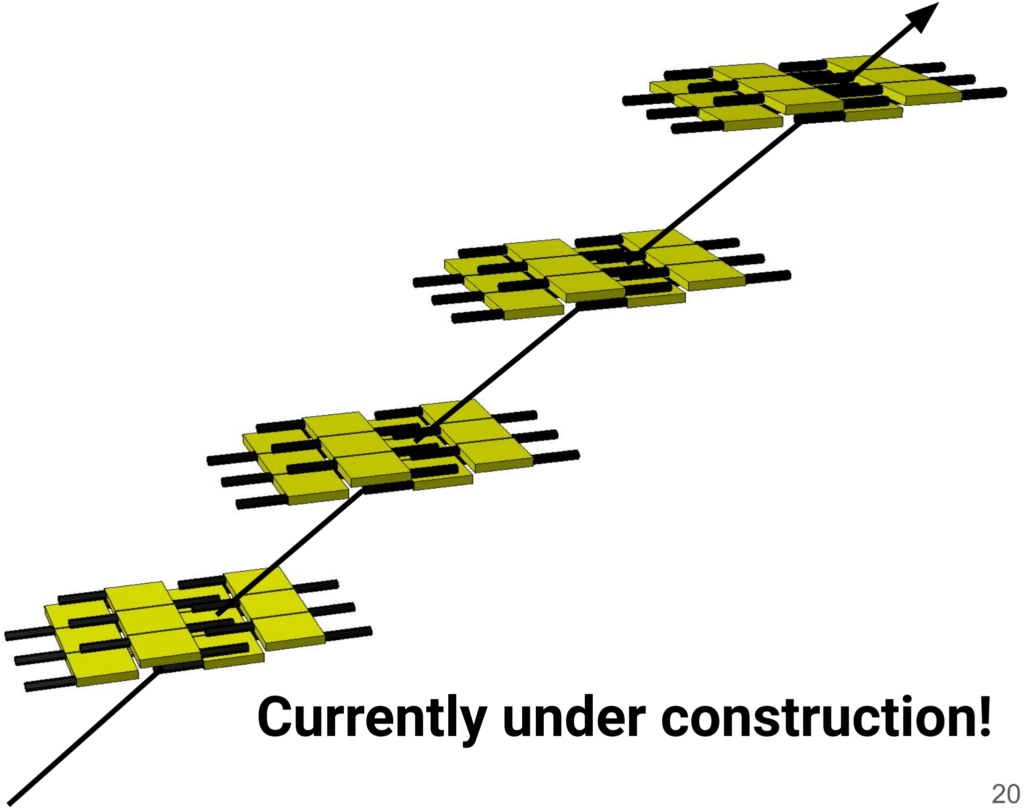
Run 3 milliQan Slab Detector design

- Twelve 40x60x5cm slabs per layer, 4 layers. Design developed and studied extensively in full simulation

- Surface area equivalent to 1100 5x5cm bars, greater in acceptance than even the HL-LHC design
    - Attacks high-mass phase space in a very efficient, targeted way

- To extend charge sensitivity, using 2 PMTs per slab

- **Huge advantage:** Modularity! We can easily modify number of layers, number of PMTs, slabs per layer, etc. Not space-limited like with bars



Currently under construction!

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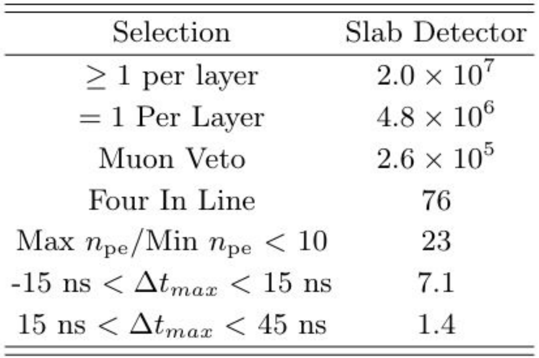
Slab Detector Background Prediction

- GEANT4 cosmic shower background predictions are made in the same way as for the bar detector
- Background rejection is strong, confined to well-defined charge region (gamma compton scatters), and even if backgrounds are higher than anticipated, can easily add more layers to improve rejection
- Will confirm with in-situ measurements after detector is installed

Run 3 Cosmic Backgrounds



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

Dark Rate ((|Δt| < 15)	0.03
Dark Rate ((|Δt| < 45)	0.7

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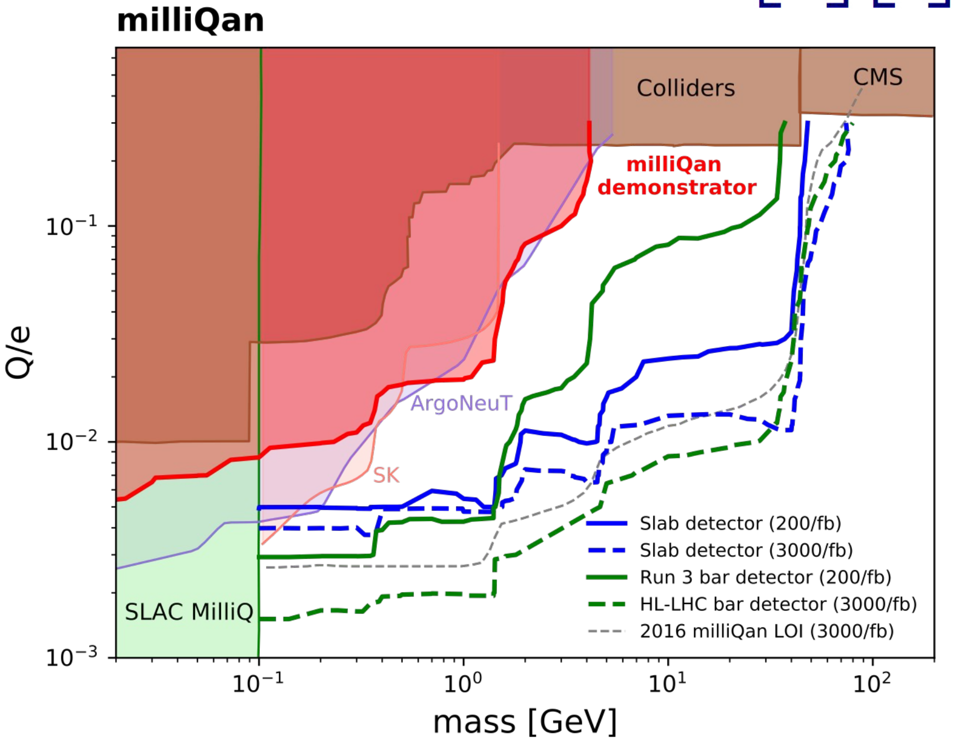
milliQan Slab + Bar Detector Sensitivity

- 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

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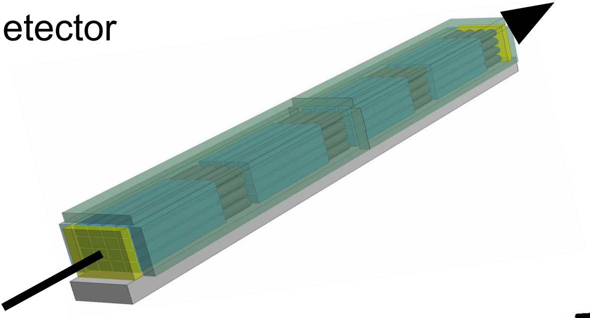
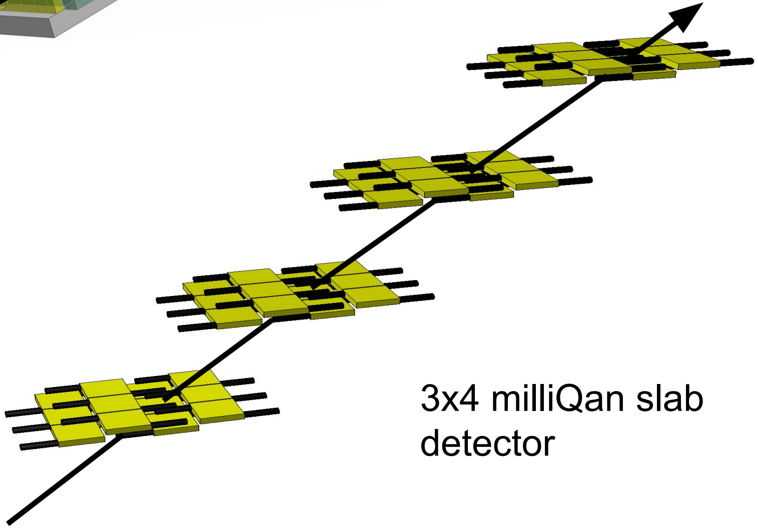
Summary

Using knowledge gained from the milliQan demonstrator, the milliQan detector designs have been updated for Run 3 and beyond to increase sensitivity and reject background

Demonstrator data has also allowed for a well-calibrated simulation to make robust background and signal predictions

The union of the **milliQan bar + slab detectors** provide exciting discovery prospects in Run 3, and both **are now under construction!**


4x4 milliQan bar detector


3x4 milliQan slab detector

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milliQan collaboration

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H. Shakeshaft

University of BRISTOL

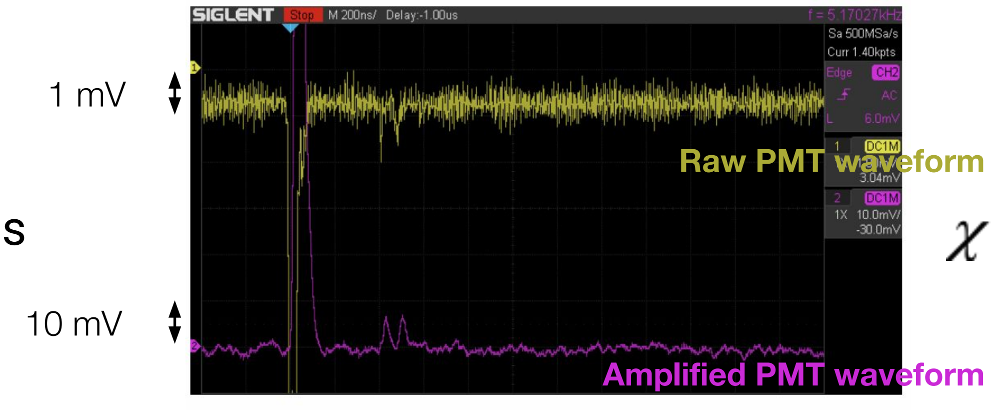
J. Brooke,
J. Goldstein

This speaker supported by
funding from DOE Office of Science

Backup: Dedicated signal amplification

We have developed new electronics to improve reconstruction of very low energy deposits

This is important because small-charge signals can deposit as little as 1 photon



Signal amplification

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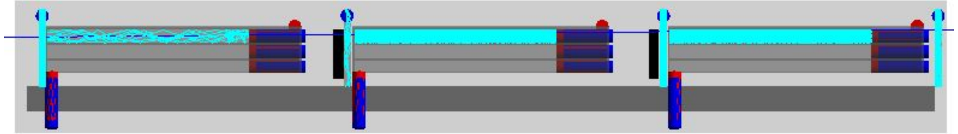
Backup - Generation Details

MadGraph5_amc@nlo - DY Processes

Light flavor mesons - Pythia8, Monash 2013 tune

Φ generation - Pythia6, DW tune



Geant4 Physics - EMStandard_option4 with Q^2 mCP energy deposition, + all relevant optical physics enabled

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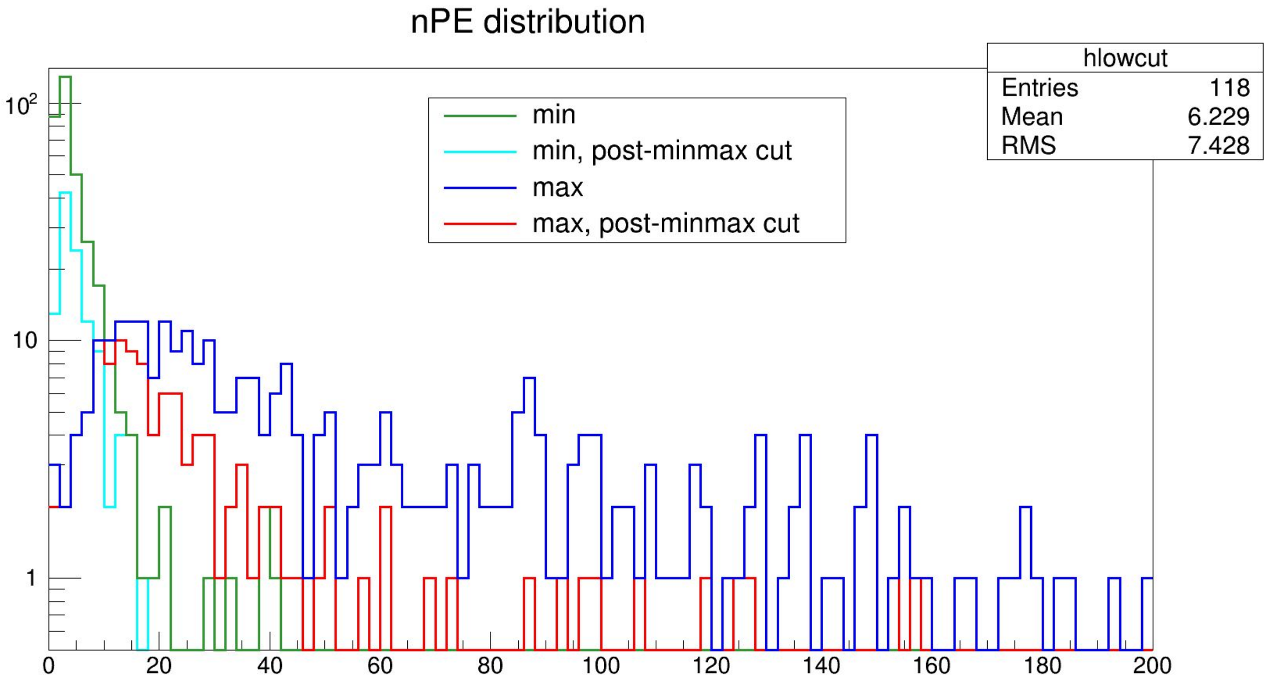
Backup: 48 slab parameters: nPE distribution, min and max

Here is a plot of two sets of min and max nPE distributions: before and after applying the max/min<10 cut

After the cut, the largest min nPE event is 39, and the vast majority of max/min nPE pairs are <30. A cut on e.g. 15 nPE in the min channel would veto >90% of these events, and a cut on 30 nPE would veto >80% of events



For a 5 inch slab, this is roughly q~.028 = 32 nPE detected. These events correspond to compton scatters from gammas

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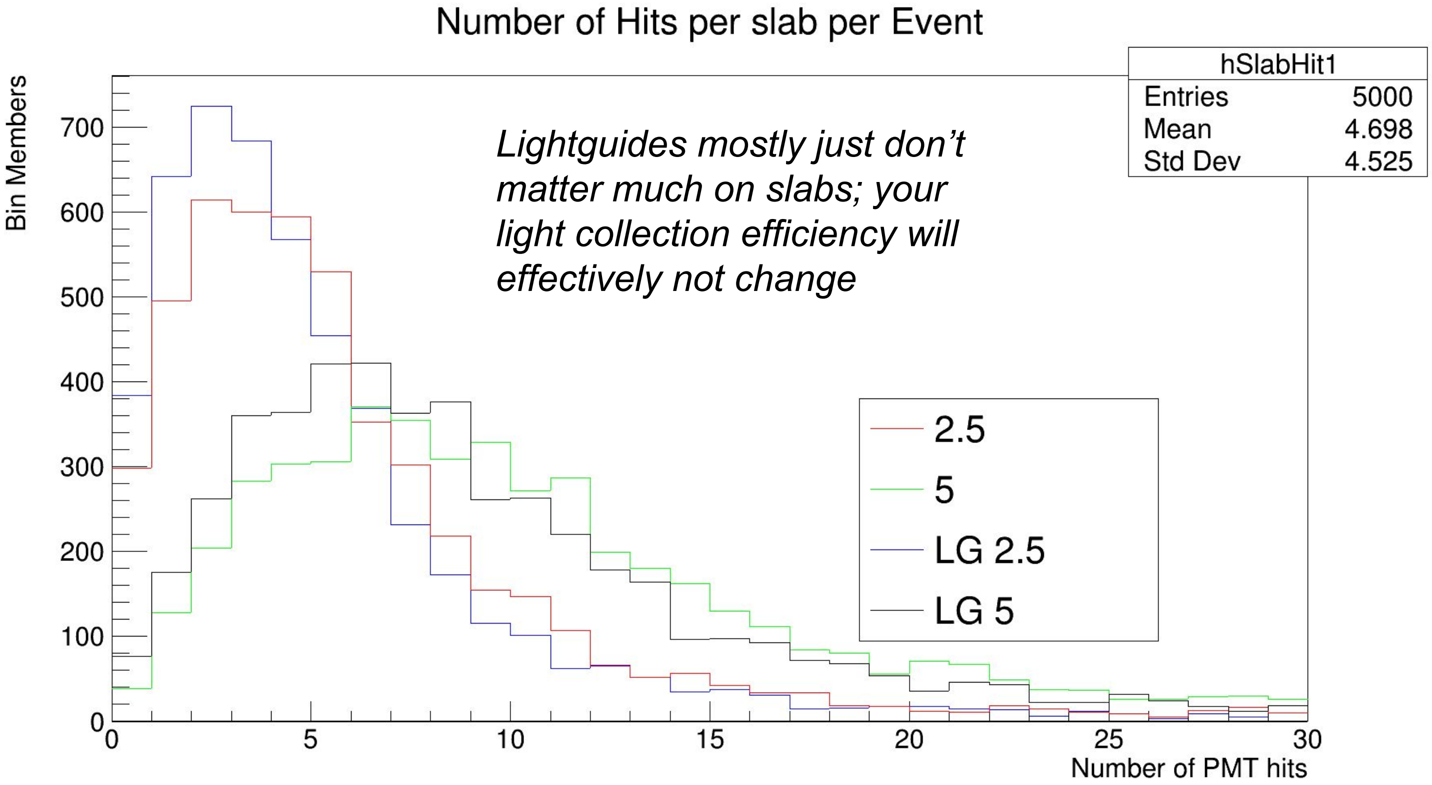
Backup: Slab nPE distribution: q=0.014

Photons go like q^2, so about a factor of 2 in charge brings the nPE up to about 30 from here

We can also *roughly* see where this region is in our preliminary signal projection...



Lightguides mostly just don't matter much on slabs; your light collection efficiency will effectively not change

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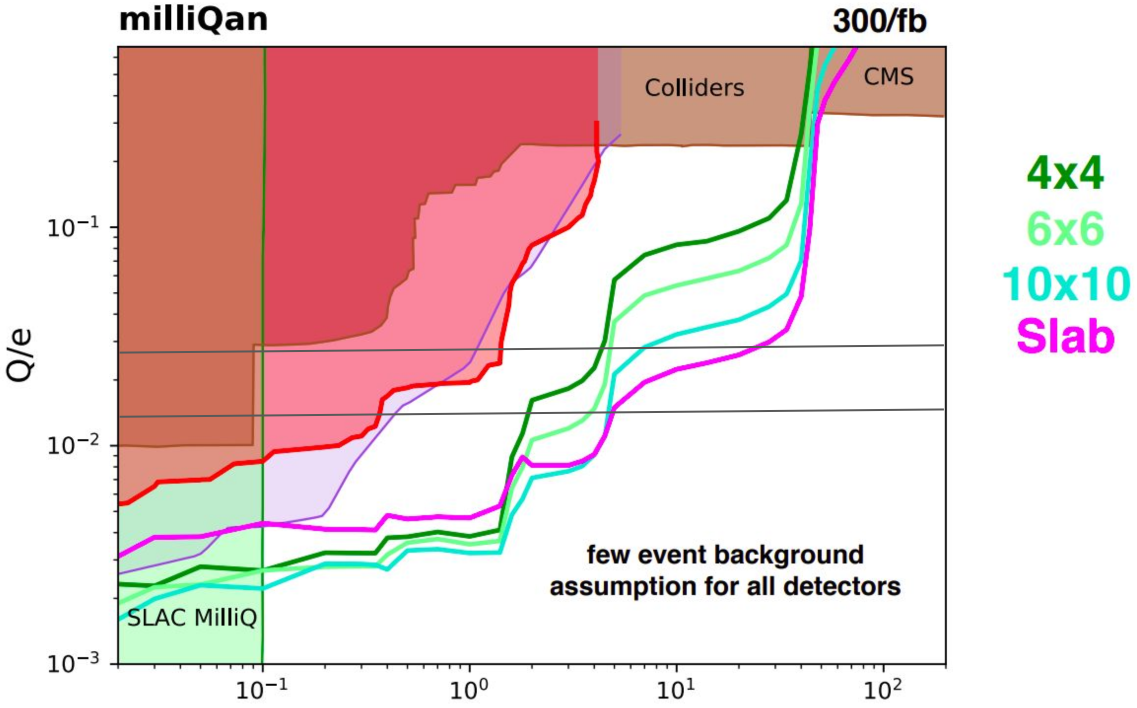
Backup: Implications on signal region

This means our cosmic background lies primarily between these two lines: 10-to-30 nPE, about 0.01e to 0.03e. Lower or higher and we can reject with increasing efficiency

We also have other SR design methods available to reject this background region, this is just an extra tool



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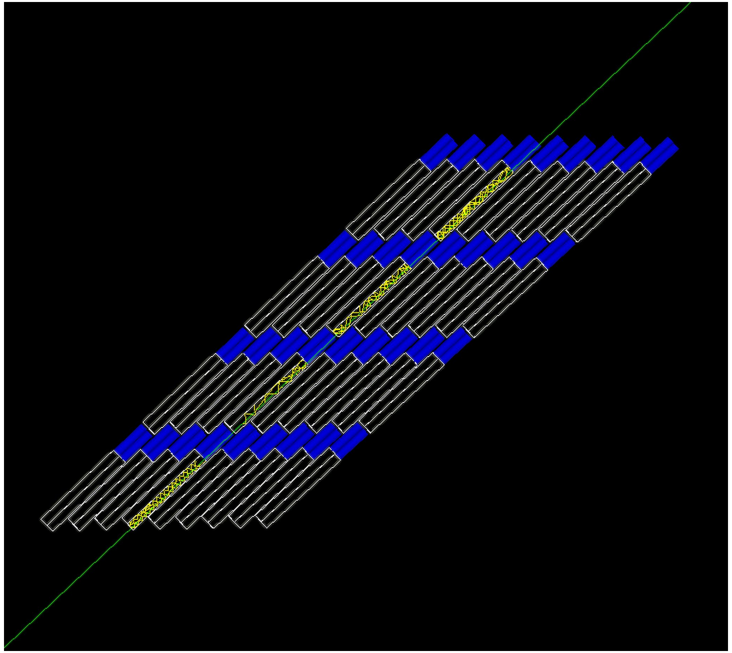
Backup: 4 layer signal visualization



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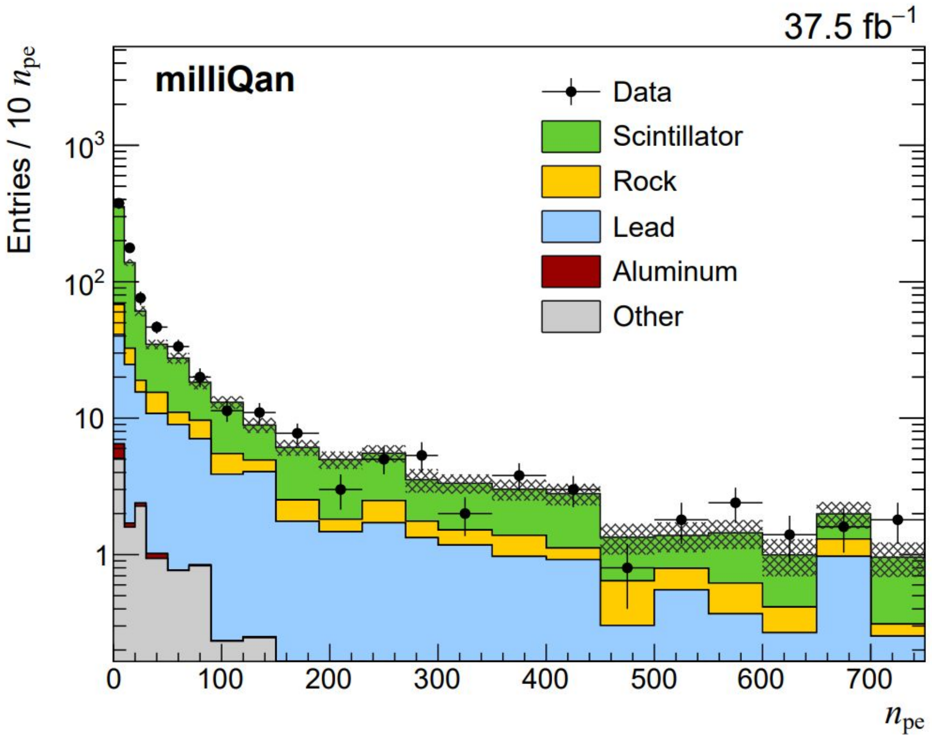
Backup - Geant4, experimental comparison

Comparison of data and simulation npe distributions in events with a tagged throughgoing beam muon, for bars that do not contain a pulse consistent with originating from a muon, and are not neighboring any such bars

Note that only 783 out of 7363 tagged muons produced detectable showers entering this figure. Simulation events are categorized based on the material in which the particle(s) that produced the pulse originated.



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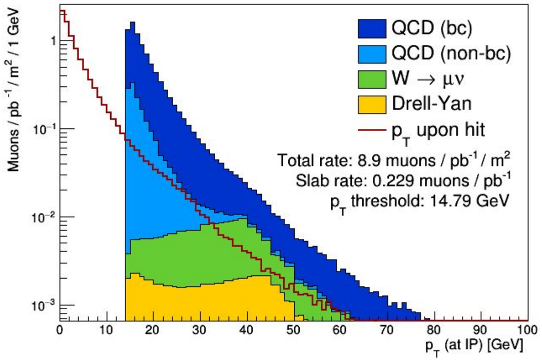
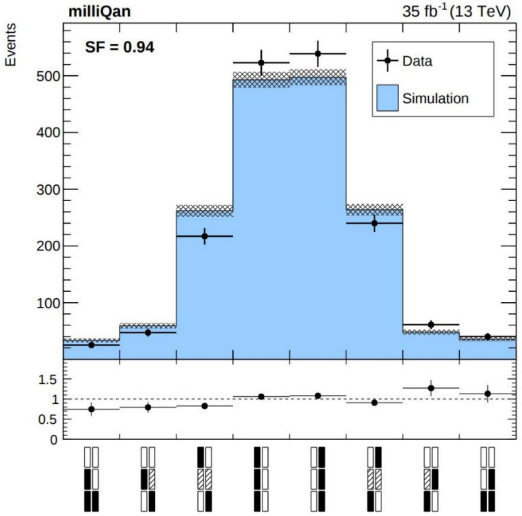
Backup: Simulation validation, more detail

- Rock shields the experiment from most beam-based particles, but muons with energy above ~15 GeV can make it to the detector
- Appear as large in-time pulses in all 4 slabs
- Also predict rate from simulation, by generating muon decays and propagating through a model of CMS magnetic field and material map
- Predicted rate from **simulation** is **0.25 ± 0.08 / pb^{-1}** (primary uncertainties from the B-hadron cross section and amount of material between IP and detector)
- Observed rate in **data** is **0.20 ± 0.01 / pb^{-1}**
- **Angular distribution** of muons is also validated





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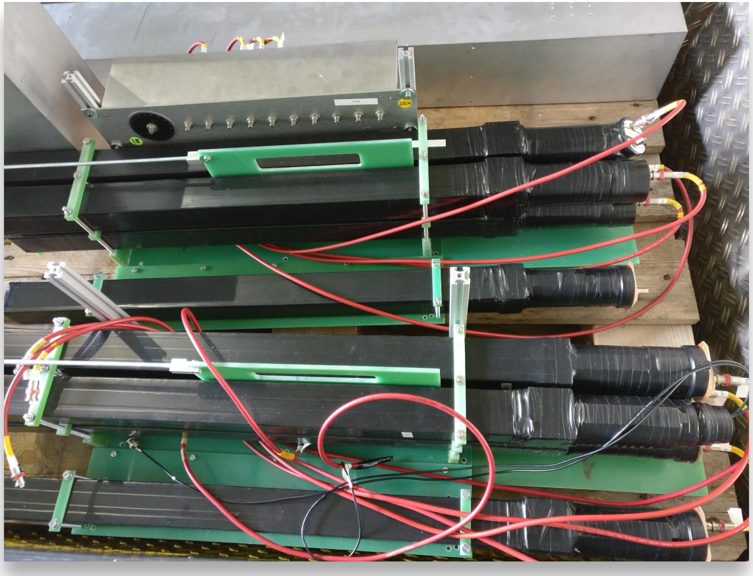
Backup - Scintillator Bar + PMT construction

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



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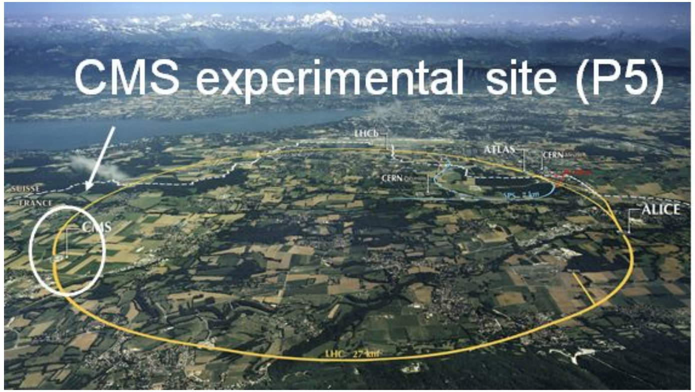
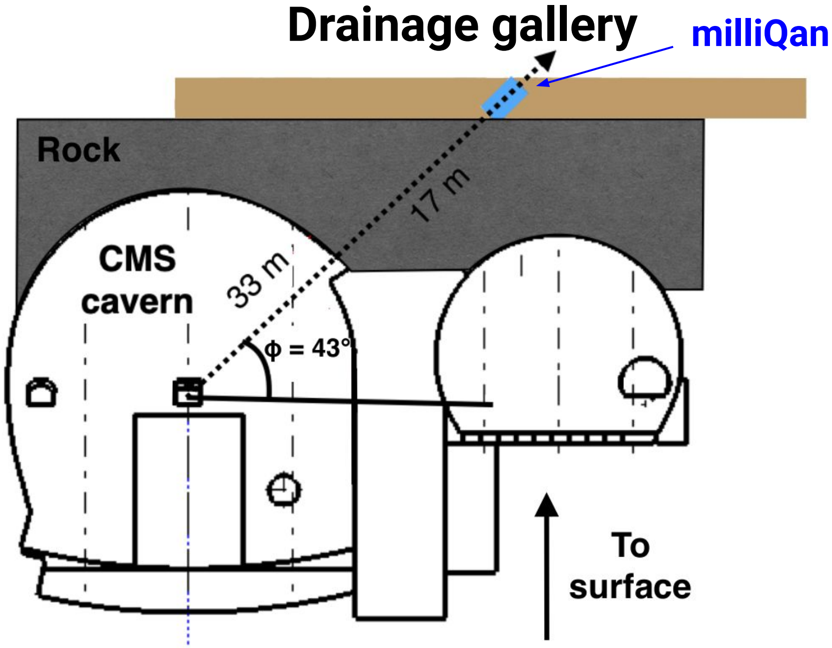
Backup: milliQan detector location

- Located in drainage gallery at LHC collision point 5 near CMS
- η ~ 0.1, 17m of rock provide natural shielding from beam particles





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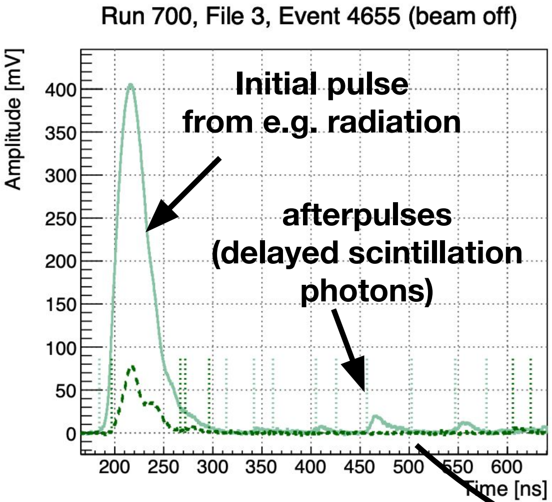
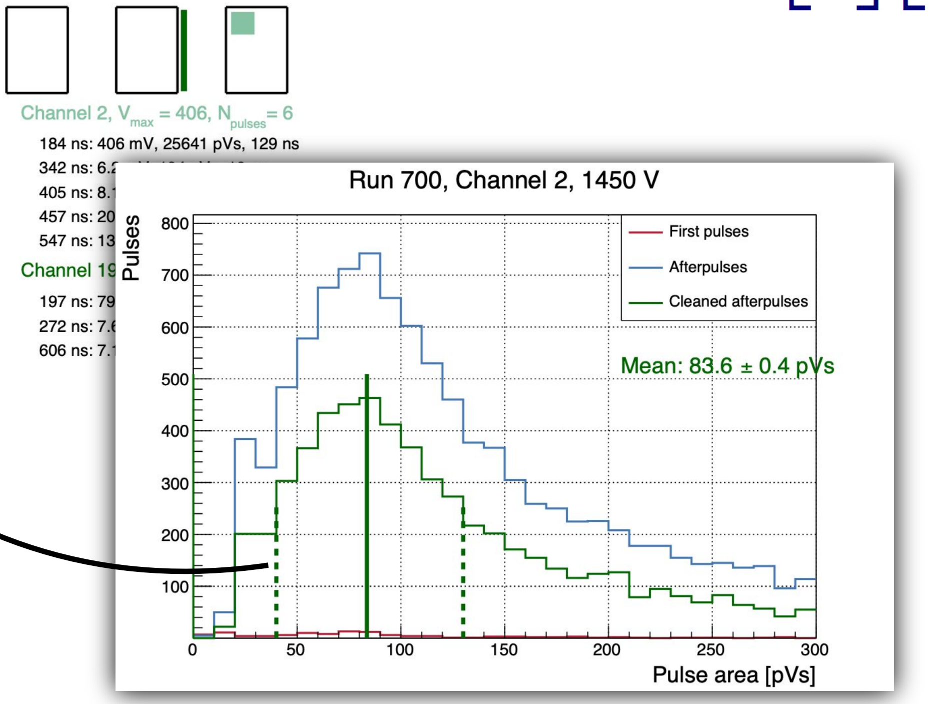
Backup - Calibration from delayed scintillation pulses



Initial pulse from e.g. radiation

afterpulses (delayed scintillation photons)



```
Channel 2, V_max = 406, N_pulses = 6
184 ns: 406 mV, 25641 pVs, 129 ns
342 ns: 6.2
405 ns: 8.1
457 ns: 20
547 ns: 13
Channel 19
197 ns: 79
272 ns: 7.6
606 ns: 7.1
```

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

e.g. R878 PMT

Mean within half-width-max gives SPE pulse area

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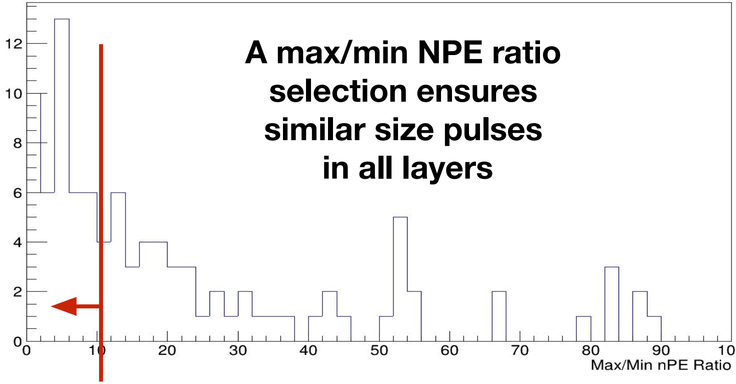
Background Prediction: Minmax and timing

Backgrounds were evaluated using this GEANT4 simulation, calibrated and validated against the four layer demonstrator, using selections motivated by the Run 2 demonstrator search

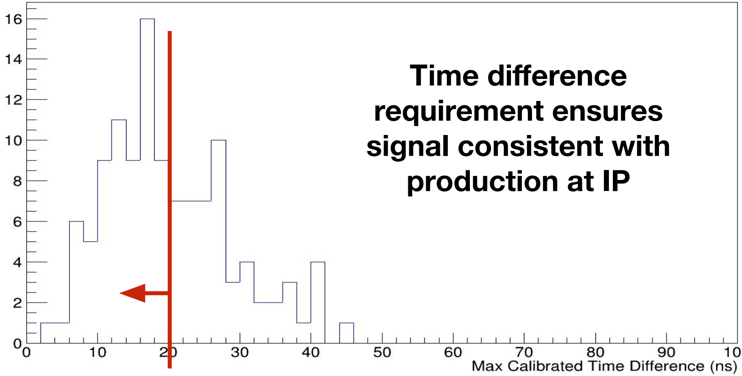
Together, these requirements reject backgrounds while maximizing signal efficiency

Cosmic Backgrounds

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}
Dark Rate	0.05	1.4



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



Time difference requirement ensures signal consistent with production at IP

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