Status of the MilliQan Experiment during Run 3

Juan Salvador Tafoya Vargas (UC Davis)
on behalf of the milliQan Collaboration

EPS-HEP 2025
Marseille

2025.07.11

New physics and dark matter → Hidden Valley

No signs of new physics seen at the LHC (yet)

SM extensions that include dark (or hidden) sectors give very plausible hint

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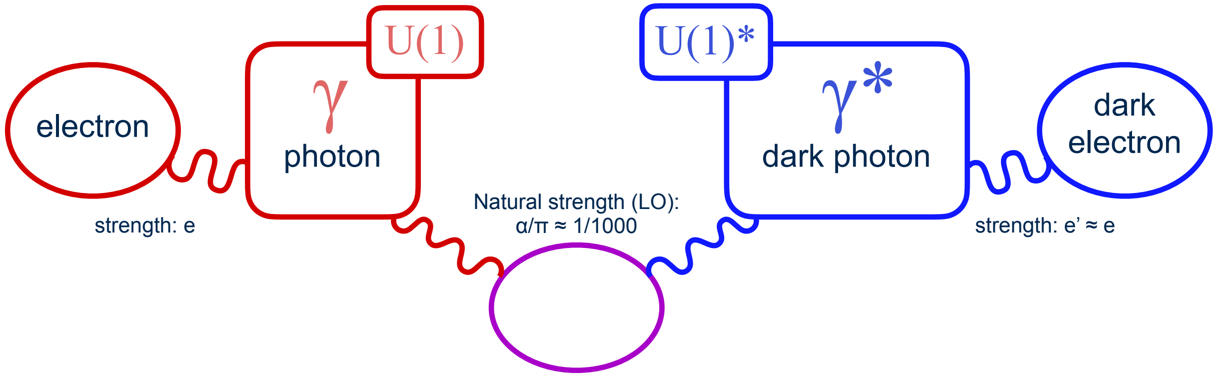
New physics and dark matter → Hidden Valley



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SM extensions that include dark (or hidden) sectors give very plausible hint

→

Photons and dark photons originate from different $U(1)$ gauge groups, but they can interact through **kinetic mixing**

Interaction with dark electrons is around **1/1000 as strong as the standard model** from naturalness arguments

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Millicharged particle searches at the LHC

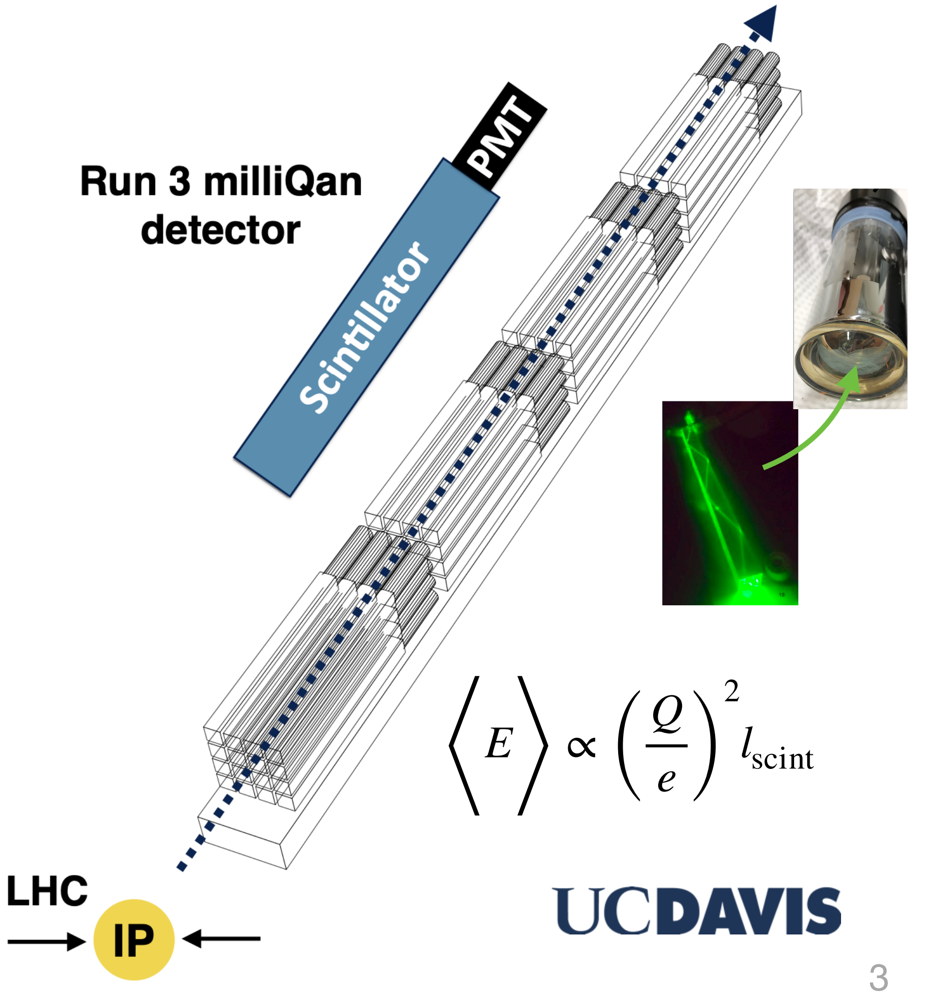
Millicharged particles (**mCPs**) are well motivated in dark sector theories, but difficult to detect because the interaction strength is reduced by a factor $(Q/e)^2$.

A complementary **LHC hidden/dark sector experiment** proposed by Andy Haas and Chris Hill in 2014

Core concept: Use array of efficient long scintillator bars + PMTs to detect ionisation from mCPs.

Challenges:

- Expect few scintillation photons to be produced
  → must be able to detect single scintillation photons
- Well controlled backgrounds → signatures "point" at the interaction point, triggering on sets of signals within small time windows (~20 ns)

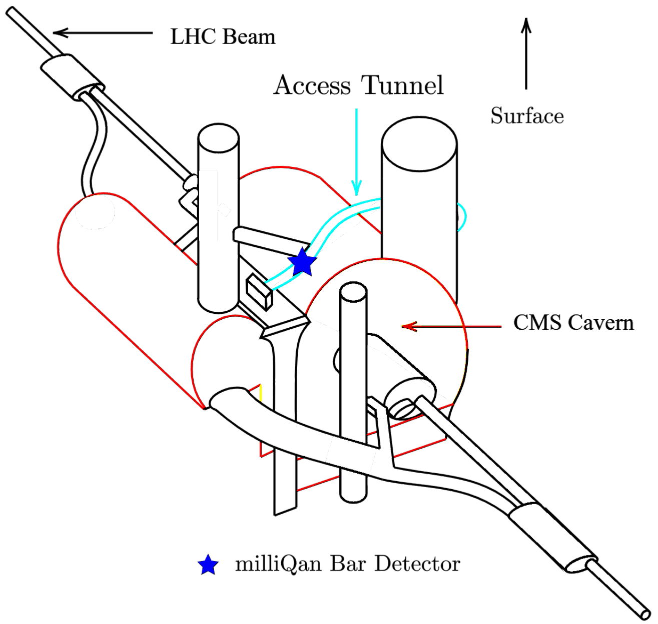


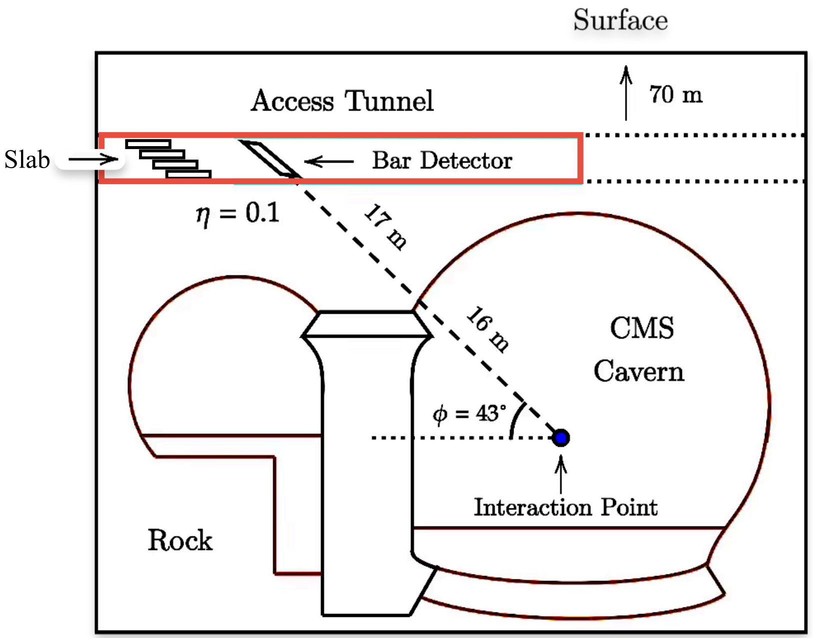
$$\left\langle E \right\rangle \propto \left(\frac{Q}{e}\right)^2 l_{\mathrm{scint}}$$

UC DAVIS

The milliQan experimental site

- In a tunnel above CMS at CERN, off-axis from LHC
  - 2 detectors, in PX56 drainage gallery
  - 33m from CMS I.P. at an angle $\eta \approx 0.1, \phi = 43$
  - 17m of rock - natural shielding from beam and I.P. subproducts
  - 70m underground - cosmic muon flux suppressed by a factor of ~100 (compared to surface)





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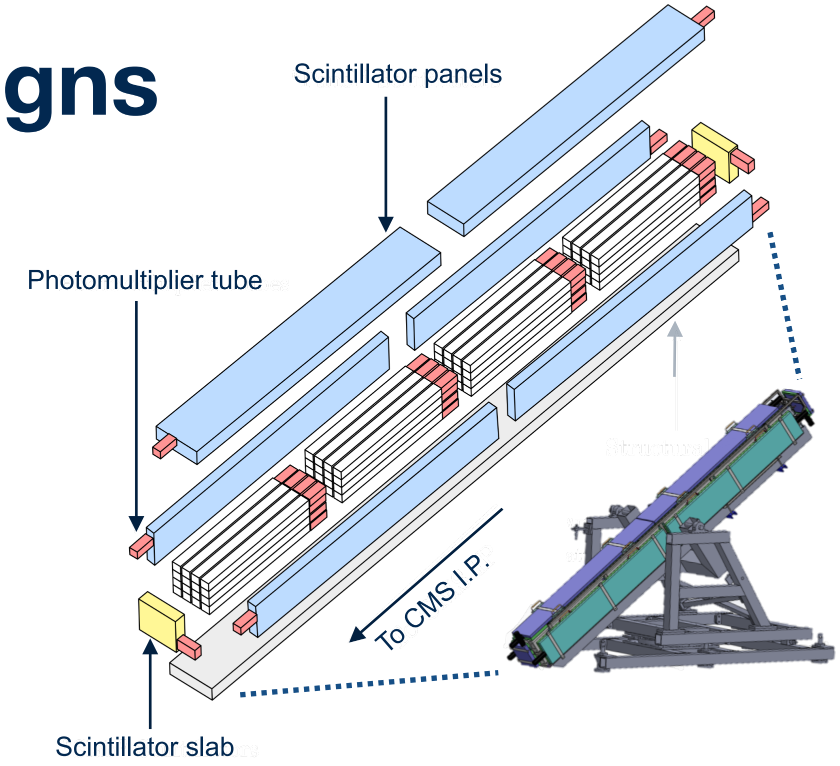
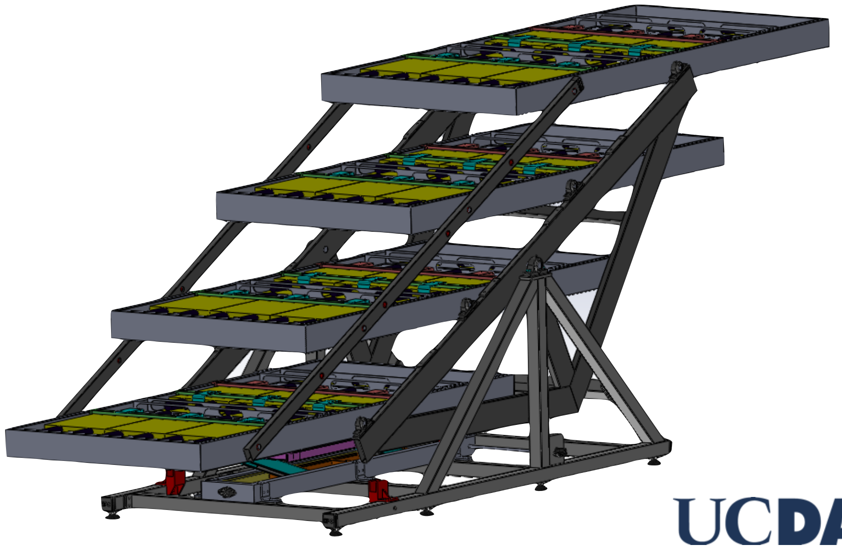
Run 3 bar & slab detector designs

- Each has 4 radial "layers" of EJ200 scintillator oriented at CMS
    - 4x4 array of 60 x 5 x 5 cm "bars"
    - Twelve 40 x 60 x 5 cm "slabs" equivalent to the coverage of **~1000 bars**
    - Coupled to Hamamatsu R878 PMTs (amplified to allow sPE sensitivity)
- Bar detector has veto panels to provide active rejection of cosmic and beam muon deposits
- DAQ uses CAEN V1743 digitizers readout by custom FPGA-based trigger board





Expected sensitivity for LHC Run 3

- Incorporating lessons learned from Run 2 bar "demonstrator," Run 3 design:
  - Added 4th layer of scintillator bars
  - Added FPGA-based trigger logic
  - Added 2nd array
- Run 3 detector is sensitive to significant region of unexplored parameter space

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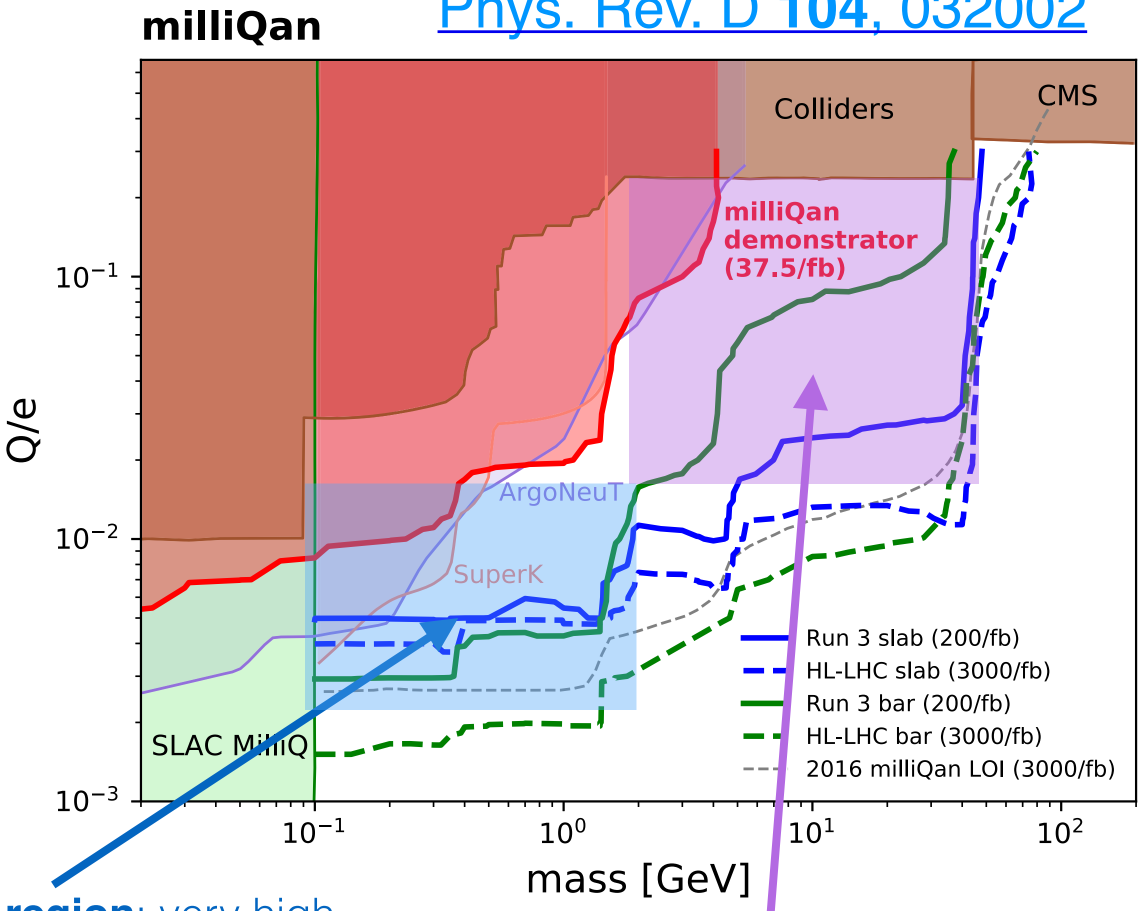

Charge limited region: very high mCP flux but low efficiency (*Bars*)

Acceptance limited region: high efficiency but mCP flux is low (*Slabs*)

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Bar detector completed in spring 2023


4 bars assembled into an unit


Wrapped with mu-metal shielding


4 units assembled into a “supermodule”

4 supermodules (64 bars) put into the cage to make the final bar detector

Slab detector completed in summer 2024

- Smoothly taking data since October 2024
- Fully commissioned now, will take physics-data remainder of 2025.

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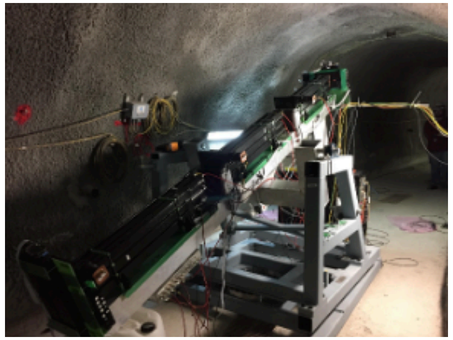
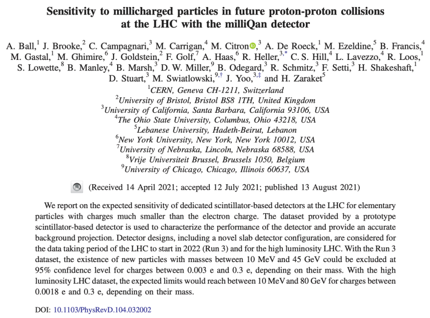
Summary of timeline



milliQan demonstrator commissioned (June 2018)



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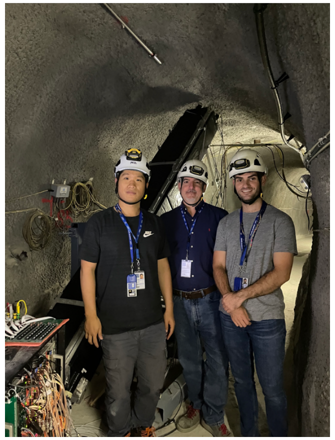
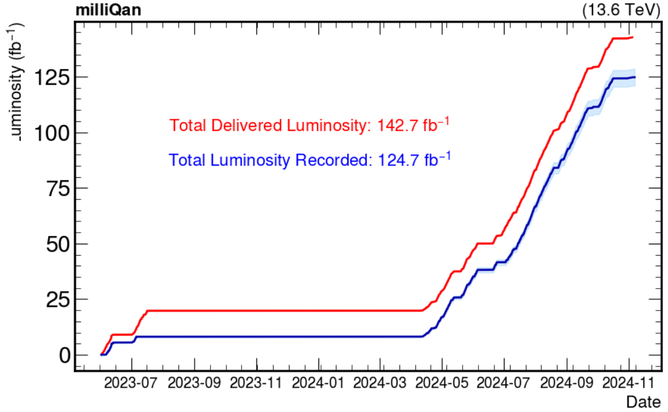
DOI: 10.1103/PhysRevD.104.032002

Run 3 projections paper (June 2023)



Bar commissioned (June 2023)



Collected $124.7\ \mathrm{fb}^{-1}$ data (Dec 2024)

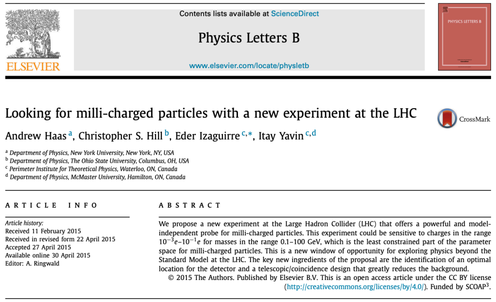
milliQan proposal (2014)

millliQan demonstrator paper (2022)

Bar detector construction begins (2022)

Slab detector commissioned (July 2022)

Bar detector search (May 2025)



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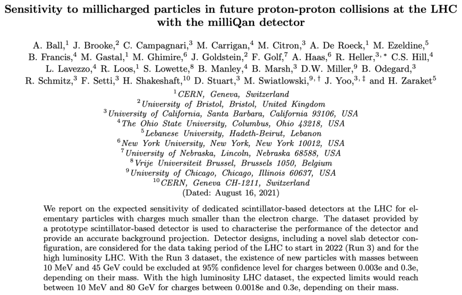

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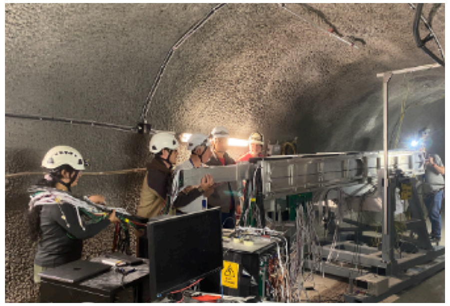

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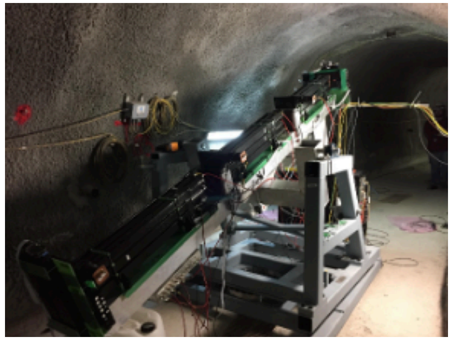

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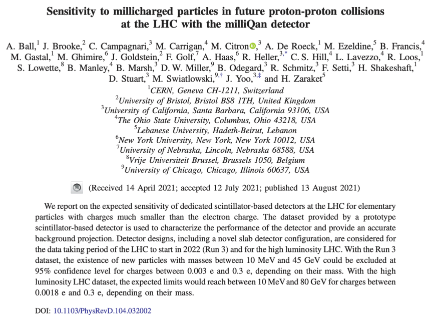

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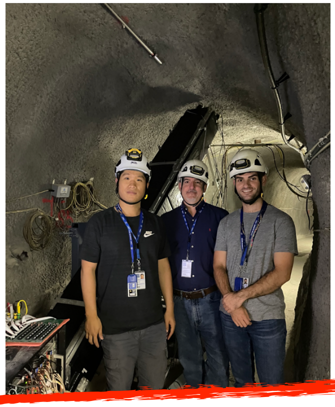

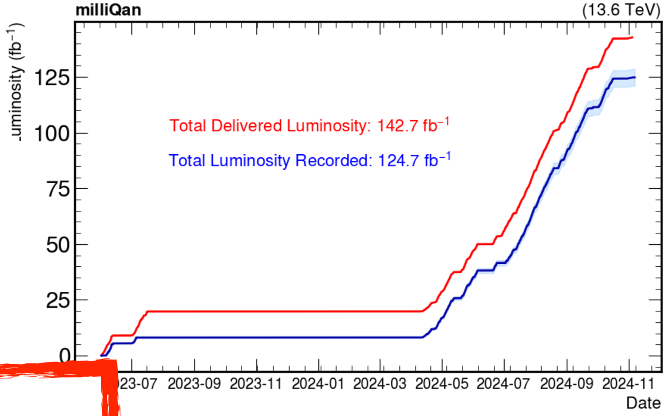

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Showing first results today!

[milliQan proposal](2014)

mil demo pa (2022)

begins (2022)

ctor ...oned (July 2022)

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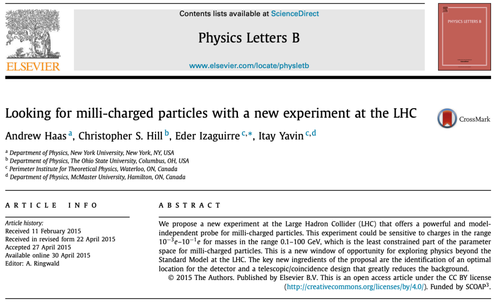

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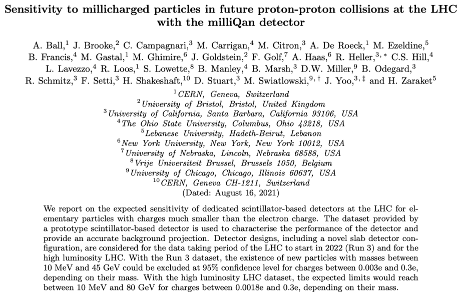

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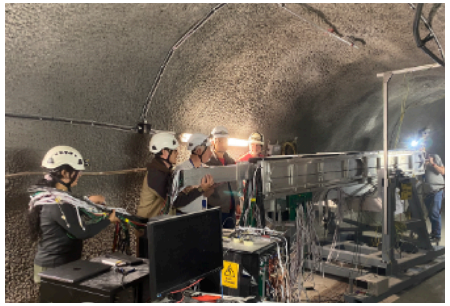

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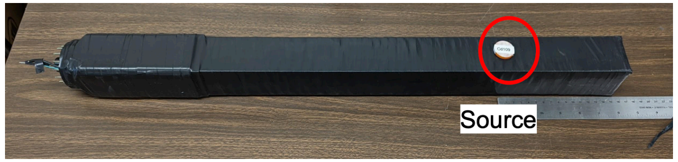
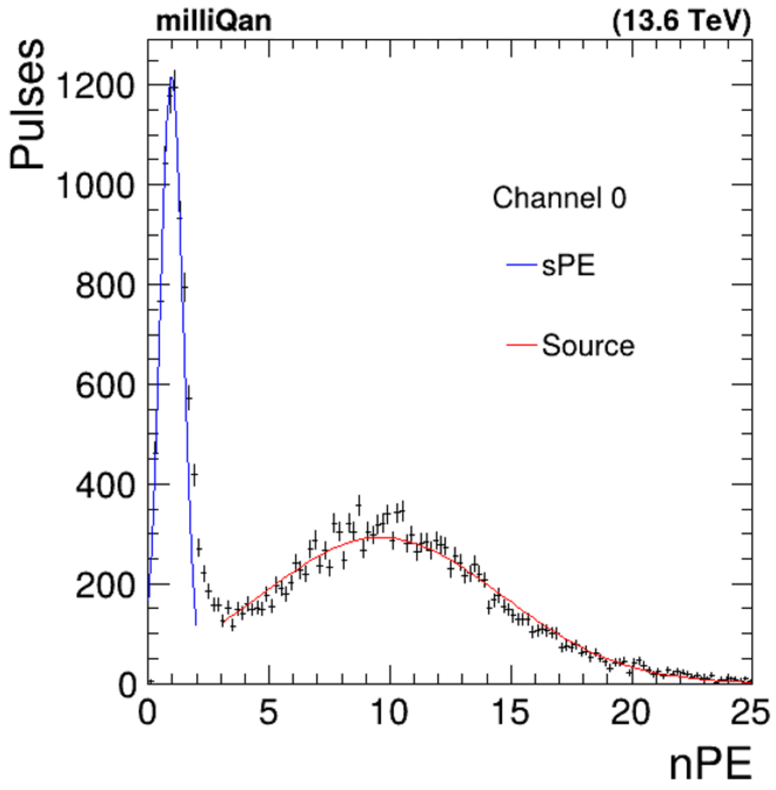
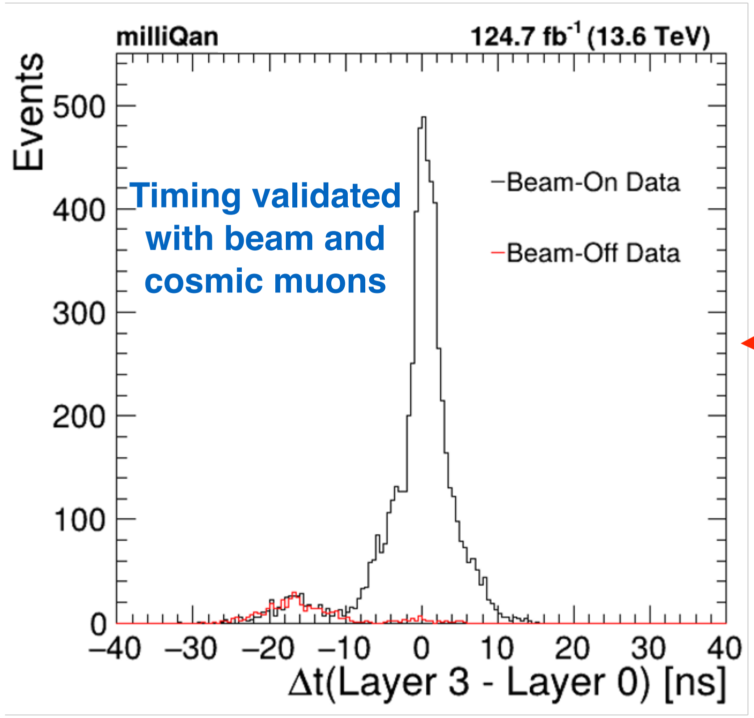
Energy and timing calibrations

- Measure response of every scintillator+PMT module using ^{109}Cd source (22 keV X-ray)
- Calibrate each channel in GEANT4 simulation to ensure accounts for differences in PMT quantum efficiency, bar wrapping, optical coupling, etc…

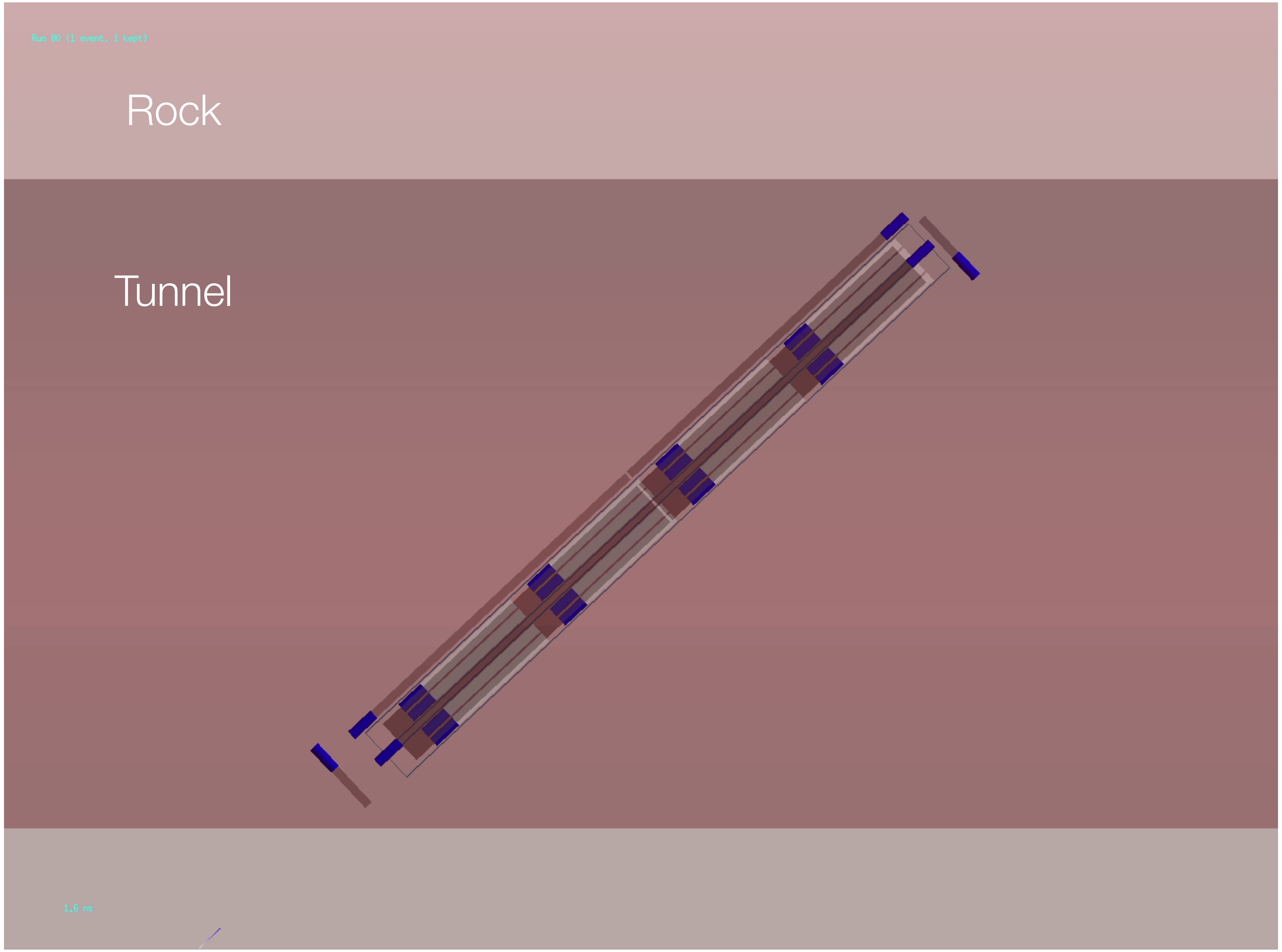






- Correct for timing shifts due to differences in electronics/cable lengths with beam on/off data + cosmic muons
  - Calibrate such that particles traveling straight through detector from I.P. have same time in all channels

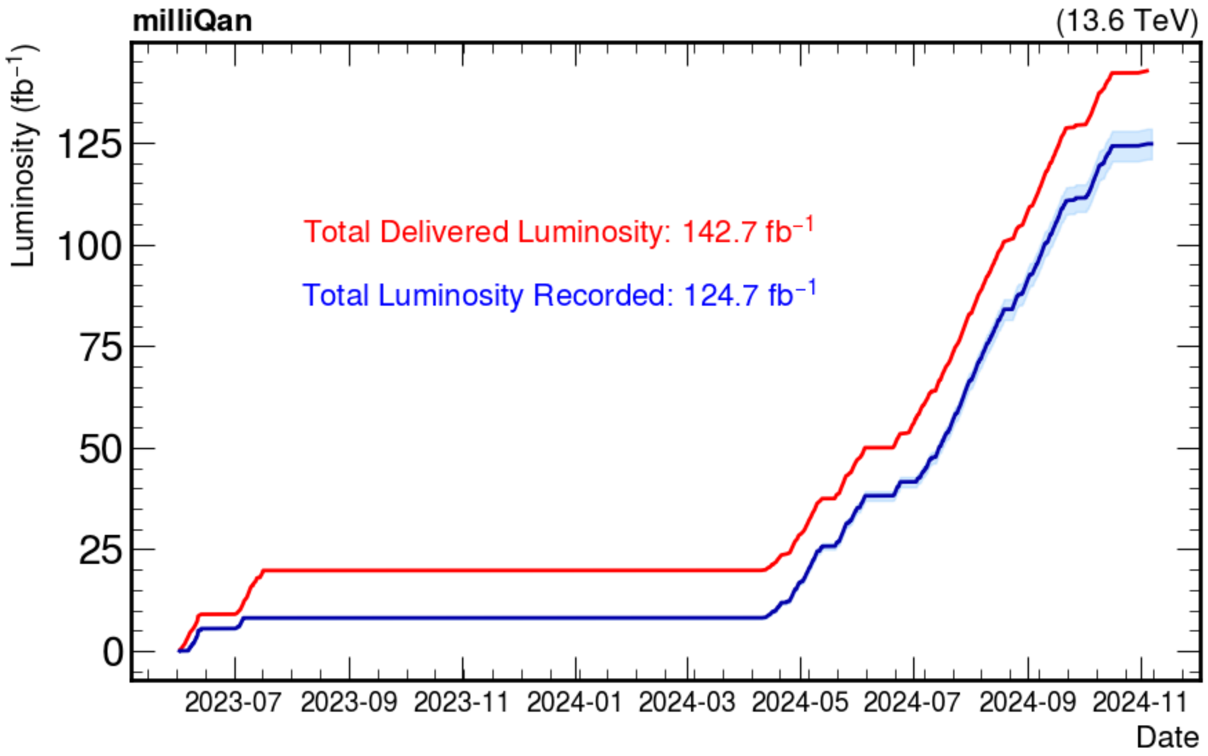
A fully calibrated GEANT simulation

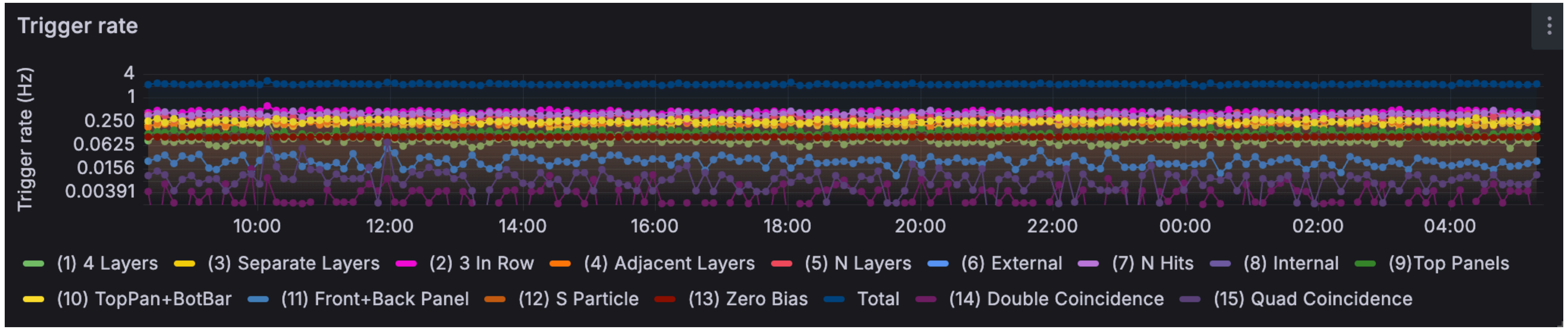


Legend:
μ, γ, mCP, e^-,
optical photon

Run 3 search for mCPs, started in 2023

- Detector and GEANT4 simulation **fully calibrated with collected data**
- Bar detector collected 124.7 fb-1 of **physics-quality** data in 7800 h of operation
- Web based DQM tools allow rapid response when issues arise
- >95% data collection efficiency since 2024!
- Carried out a first search for the mCPs with this dataset





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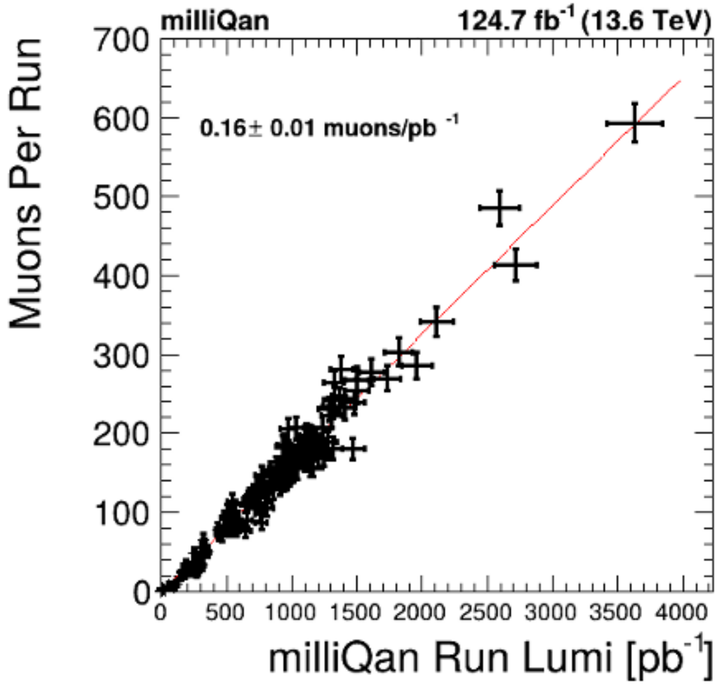
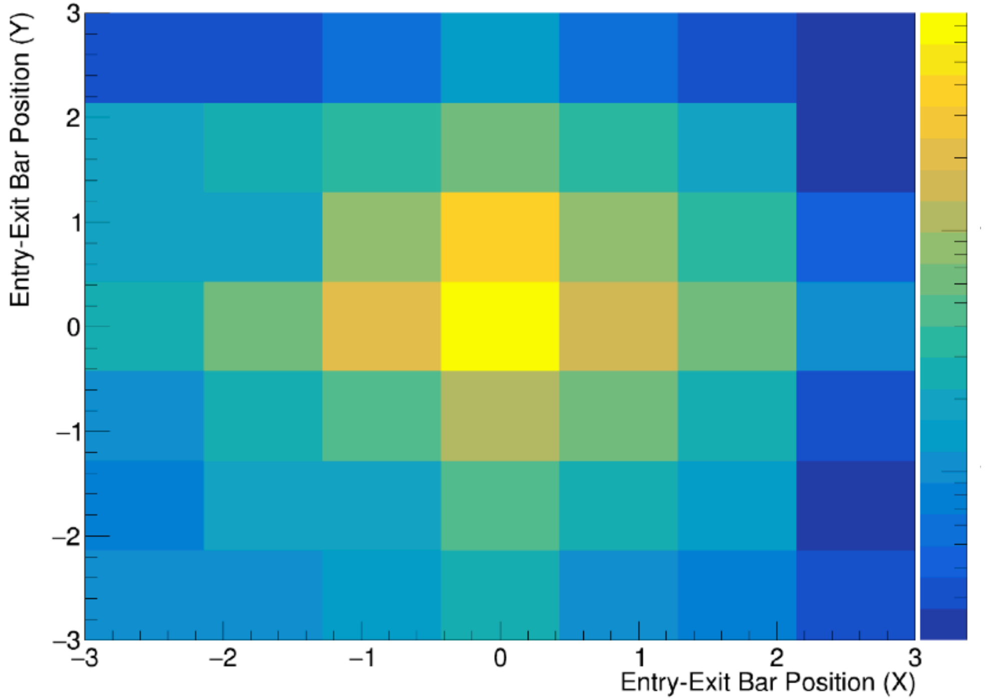
Validating simulation and alignment with muons

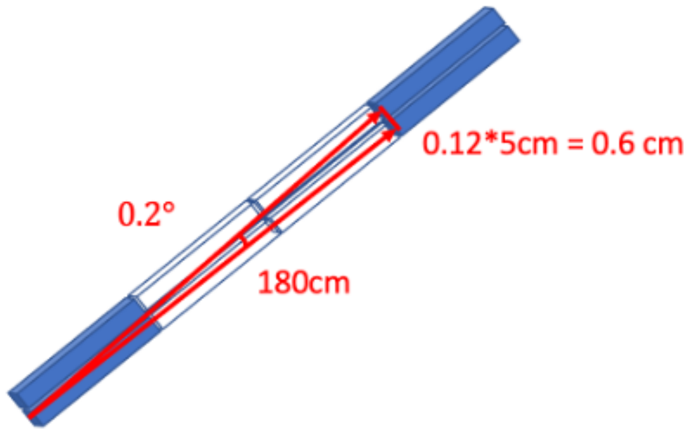
Muon rates



Alignment



measured ~0.2° misalignment



Fixing for 2025 running!

- Using paths of muons measure ~0.2° misalignment
  → correcion applied to MC (~12% impact on signal a efficienty)

- Measured muon rate in agreement with simulation:
  obserbed $0.21 \pm 0.05\ \mathrm{pb}^{-1}$ for $0.21 \pm 0.05\ \mathrm{pb}^{-1}$ expected

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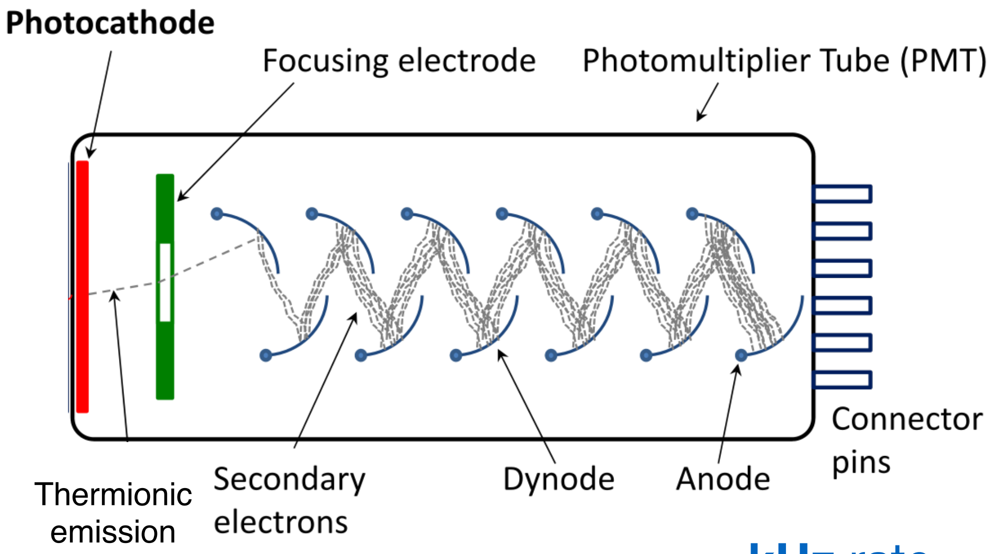
Main mCP backgrounds + mitigation

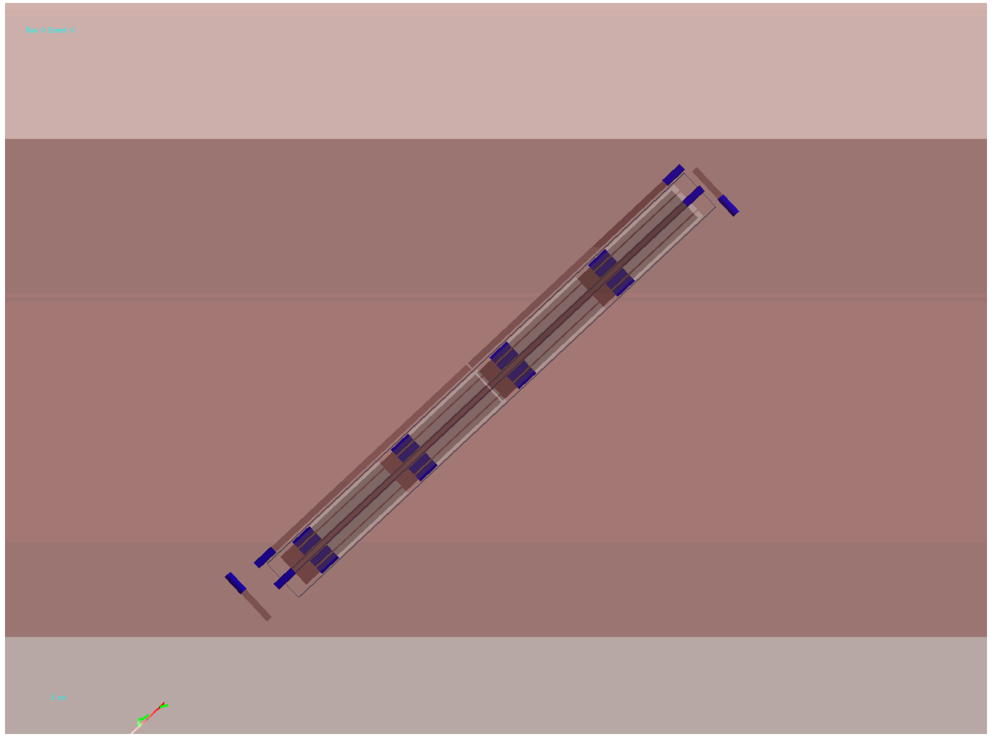
Background: PMT dark rate (random in time)



~ **kHz** rate

Require 4 layer coincidence
(hit in **each layer** within **20 ns window)**

Background: beam/cosmic muon + secondaries



Veto events with **single** deposit per layer forming **pointing path** to I.P. **if** also have **deposits in side panels**

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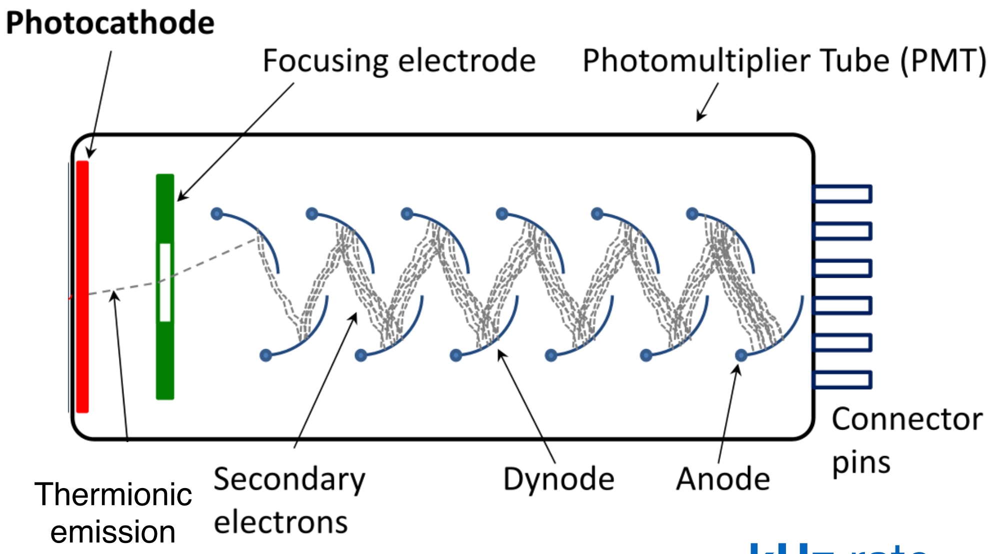
Main mCP backgrounds + mitigation

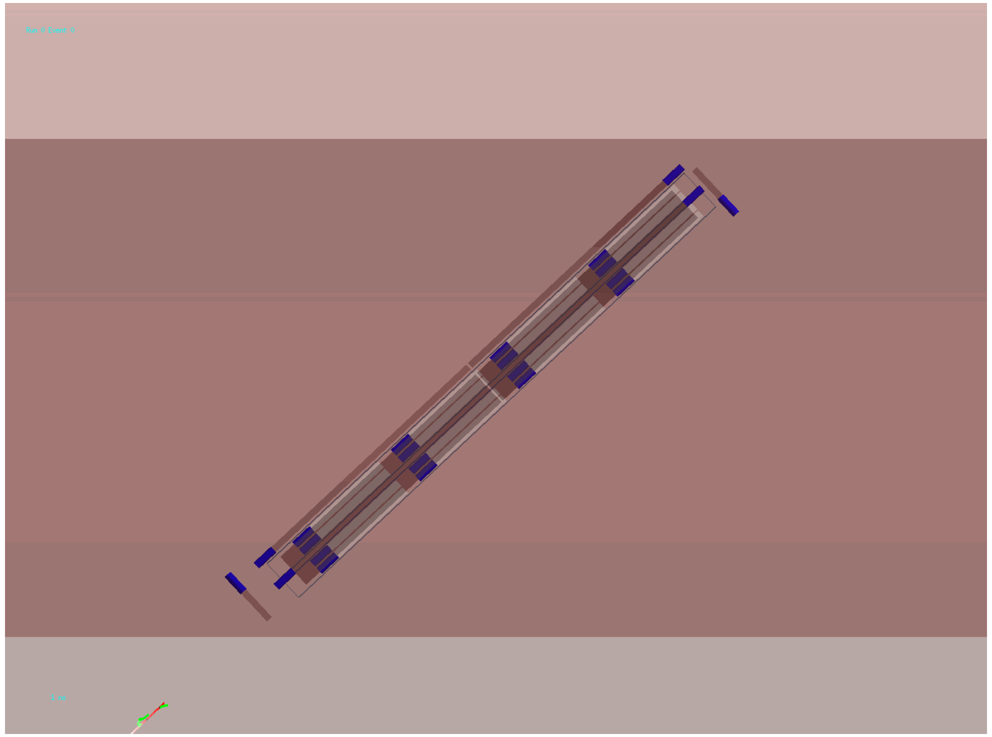
Background: PMT dark rate (random in time)



~ **kHz** rate

Require 4 layer coincidence
(hit in **each layer** within **20 ns window)**

Background: beam/cosmic muon + secondaries



Veto events with **single** deposit per layer forming **pointing path** to I.P. **if** also have **deposits in side panels**

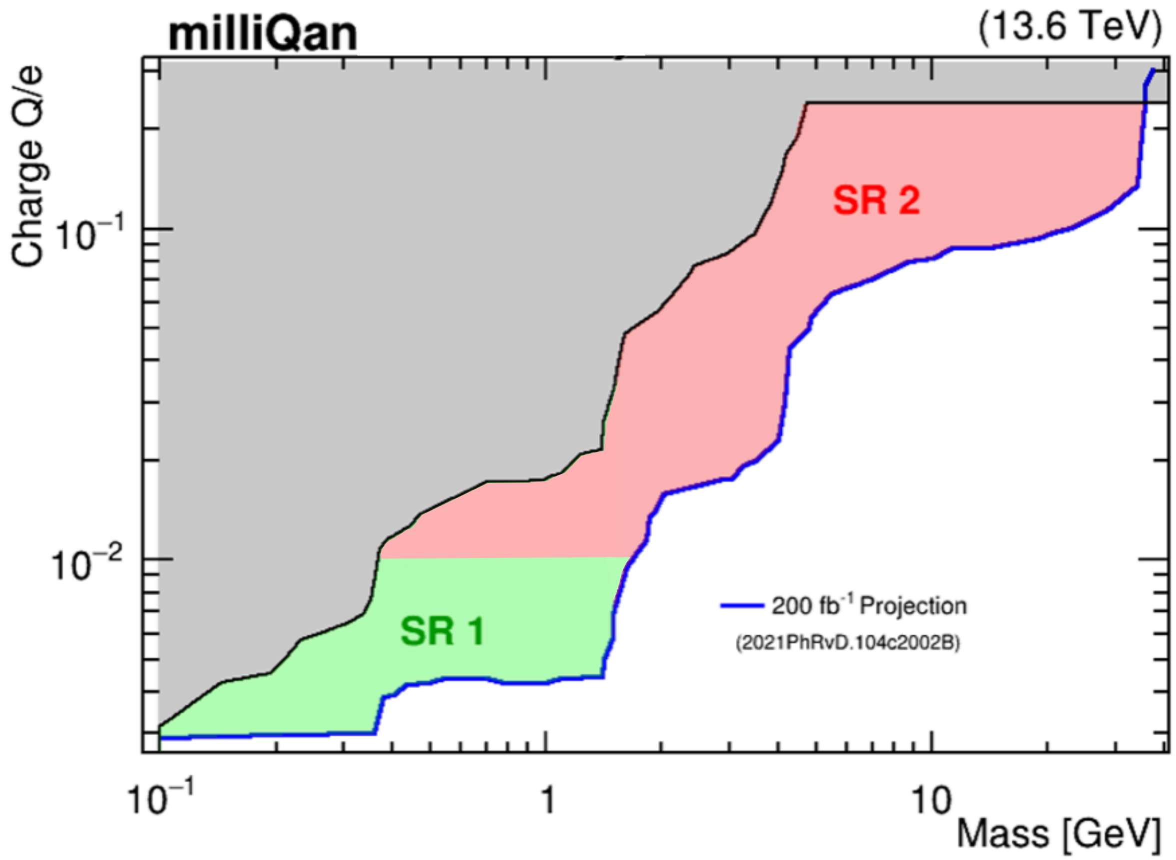
Search in two orthogonal signal regions

SR1: lower charges

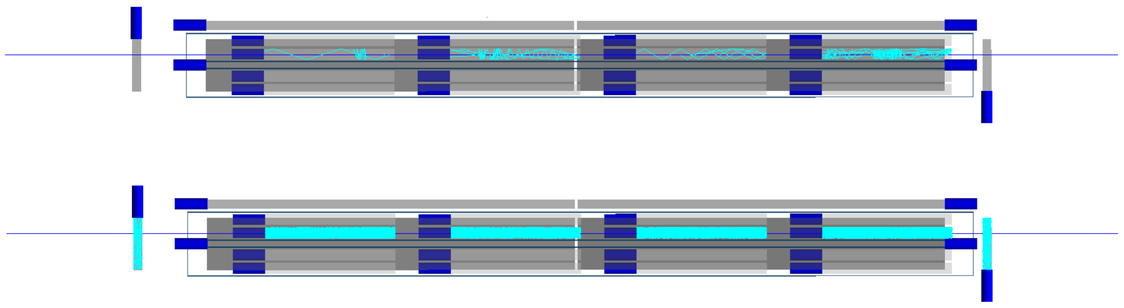
- **Veto** events with hits in **front/back panels** and **saturating pulses** deposited in any bar.

SR2: higher charges

- **Require** events to have **≥1** hits in **front/back panel** (but with < 70 nPE).



Q/e = 0.002



SR1

Q/e = 0.01

SR2

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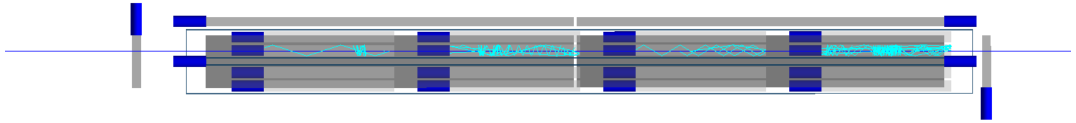
Background prediction/validation: SR1

Q/e = 0.002



Background predicted using ABCD method inverting **timing** and **pointing path** requirements in “beam-on” dataset (data taken during LHC collisions).

Validate prediction method using **beam-off** dataset and “**nearly pointing**” **control region** (max deviation from straight-path of one bar/layer).

Beam-off SR1

Prediction: $0.32^{+0.24}_{-0.16}$
Observation: 0

Beam-on SR1 control region

Prediction: $0.31^{+0.28}_{-0.18}$
Observation: 1

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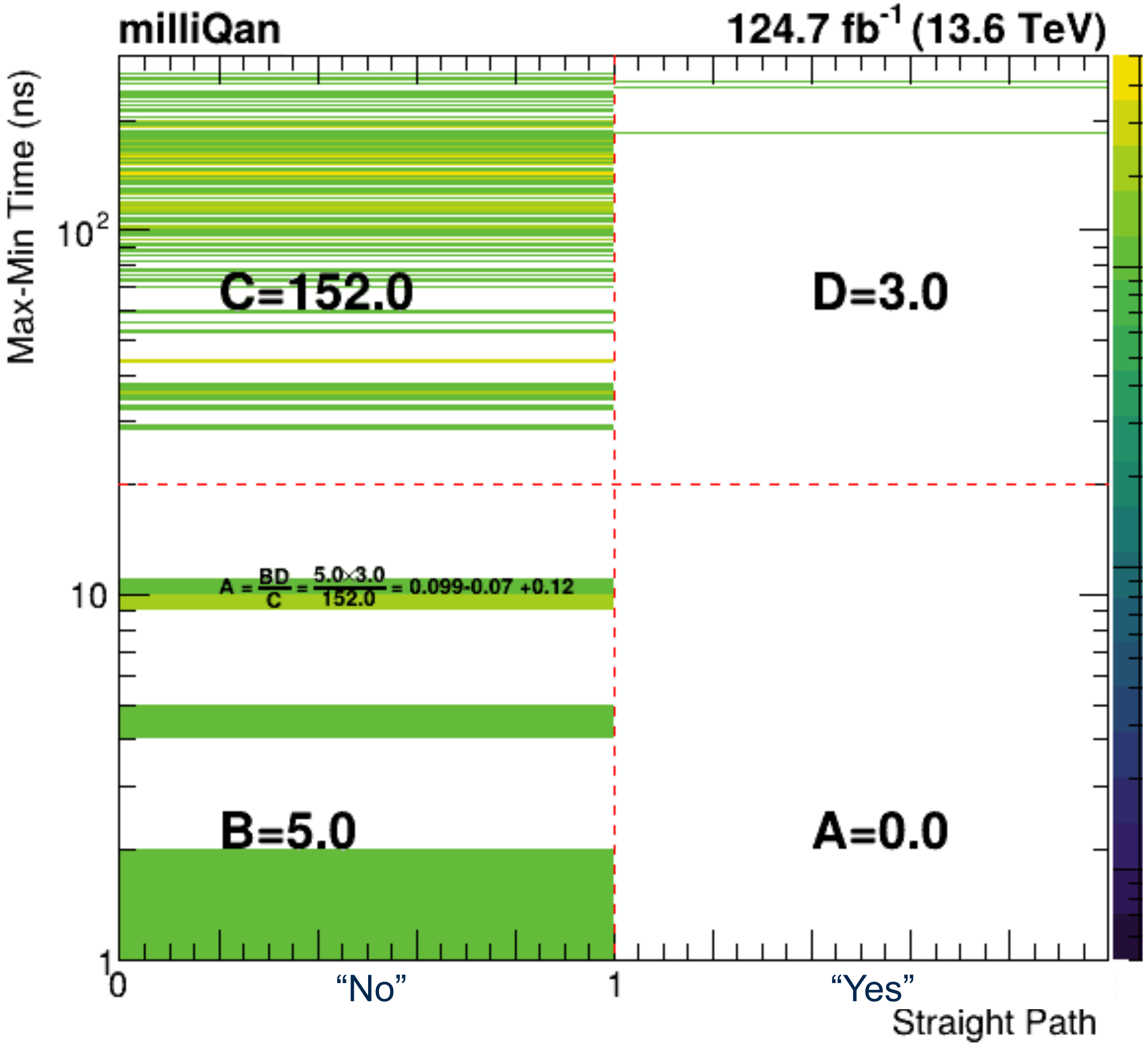
SR1 search results

- Prediction: $0.10^{+0.12}_{-0.07}$
- Observation: 0

Result:
Observation consistent with background expectation

No mCP signal :(



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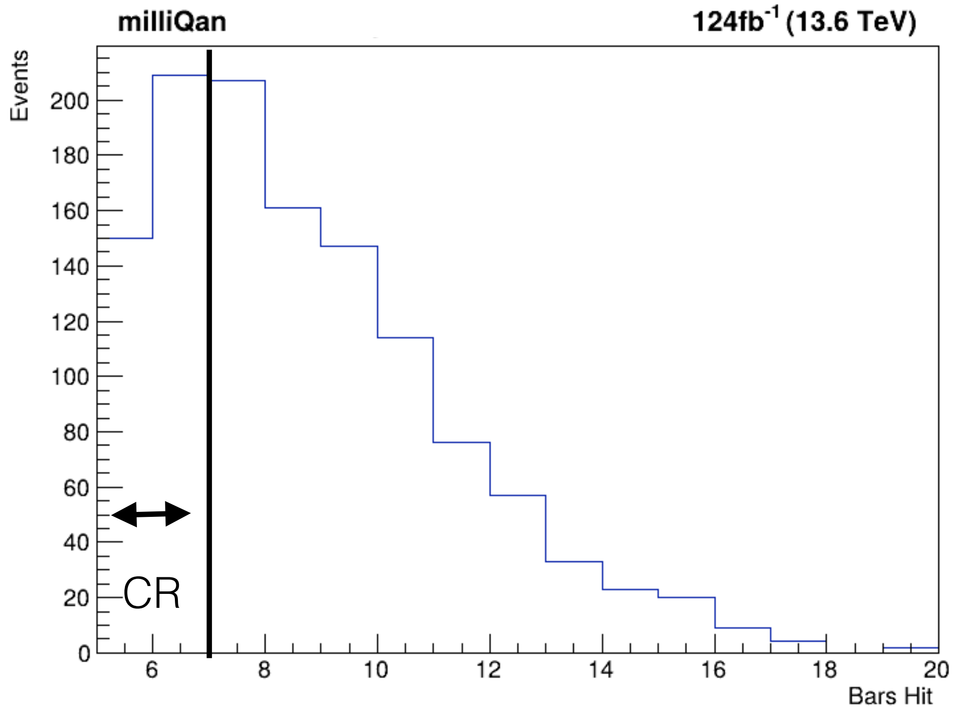
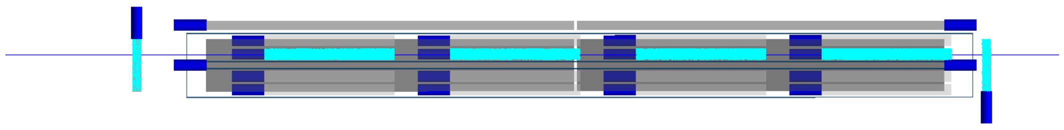
Background prediction/validation: SR2

- Dominant background for SR2 is from beam muons that shower through detector — can't predict in beam-off dataset
- Background predicted using ABCD method inverting front/back panel nPE and number of bar requirements
- Validate prediction method using 5-6 bar hit control region



Q/e = 0.01



Beam-on SR2 control region

Prediction: $3.40^{+1.69}_{-1.20}$

Observation: 5

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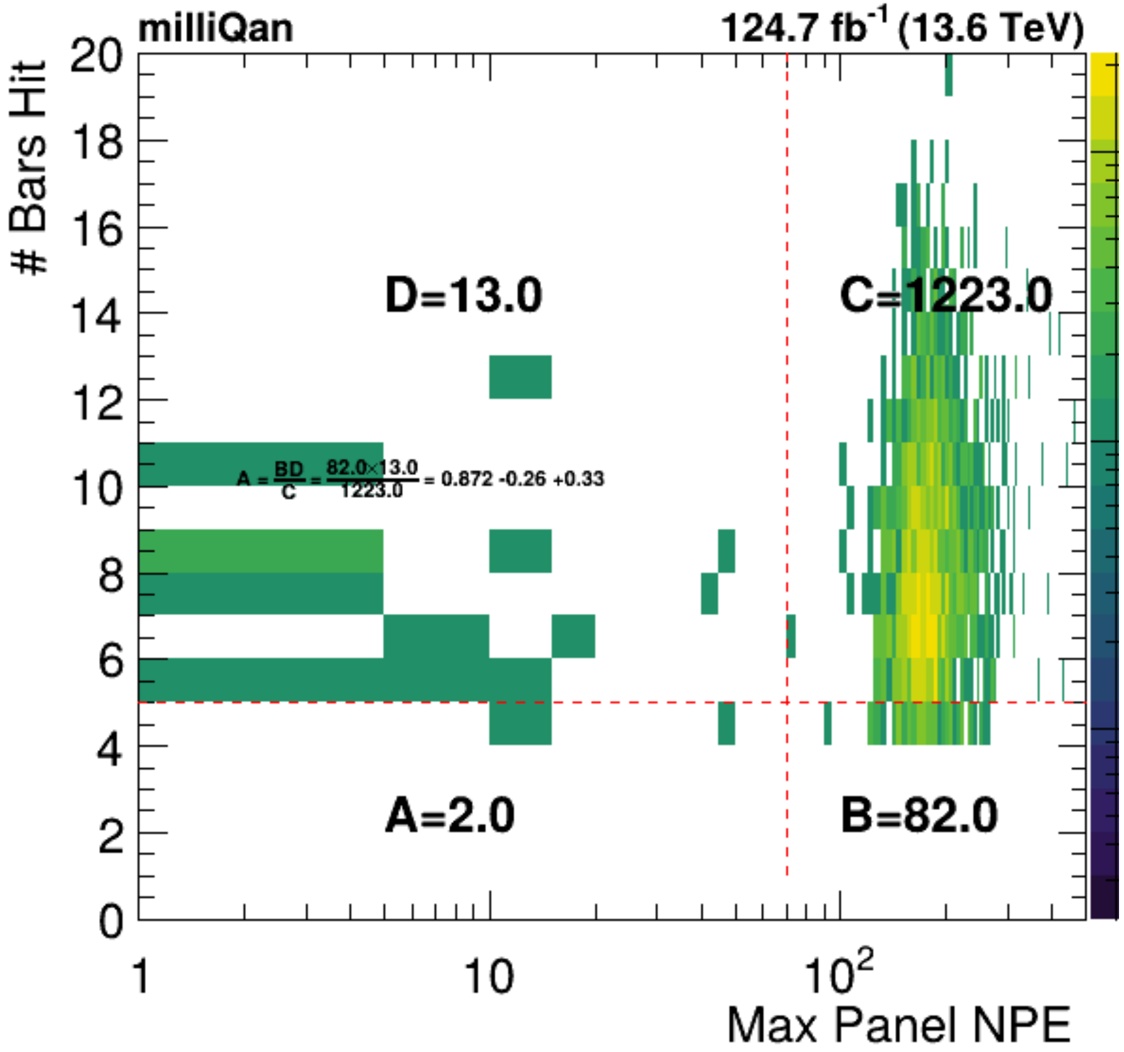
SR2 search results

- Prediction: $0.87^{+0.33}_{-0.26}$
- Observation: 2

Result:
Agreement within ~1.2σ



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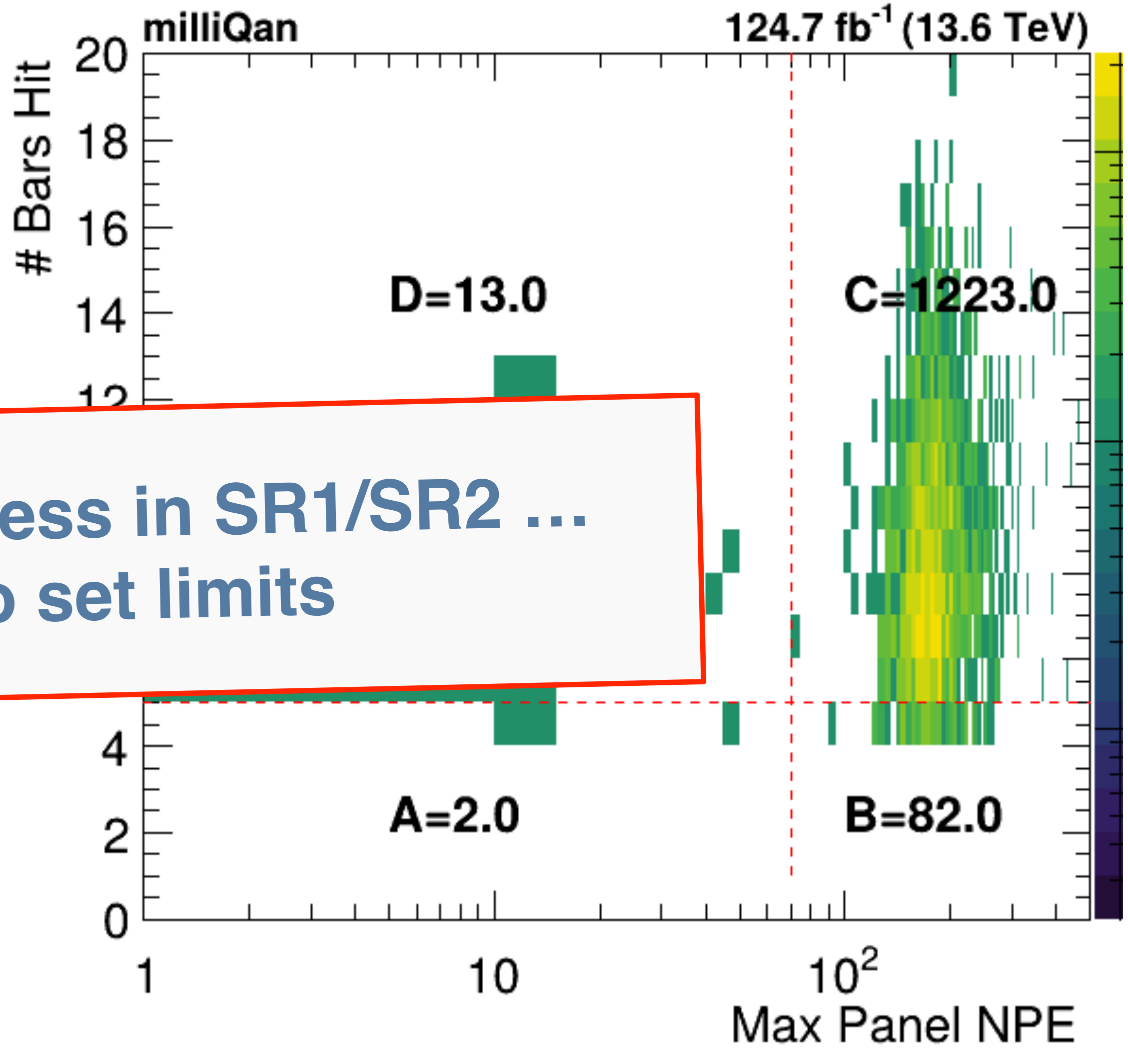
SR2 search results

- Prediction: $0.87^{+0.33}_{-0.26}$
- Observa

No significant excess in SR1/SR2 …
proceed to set limits

Result:
Agreement within ~1.2σ



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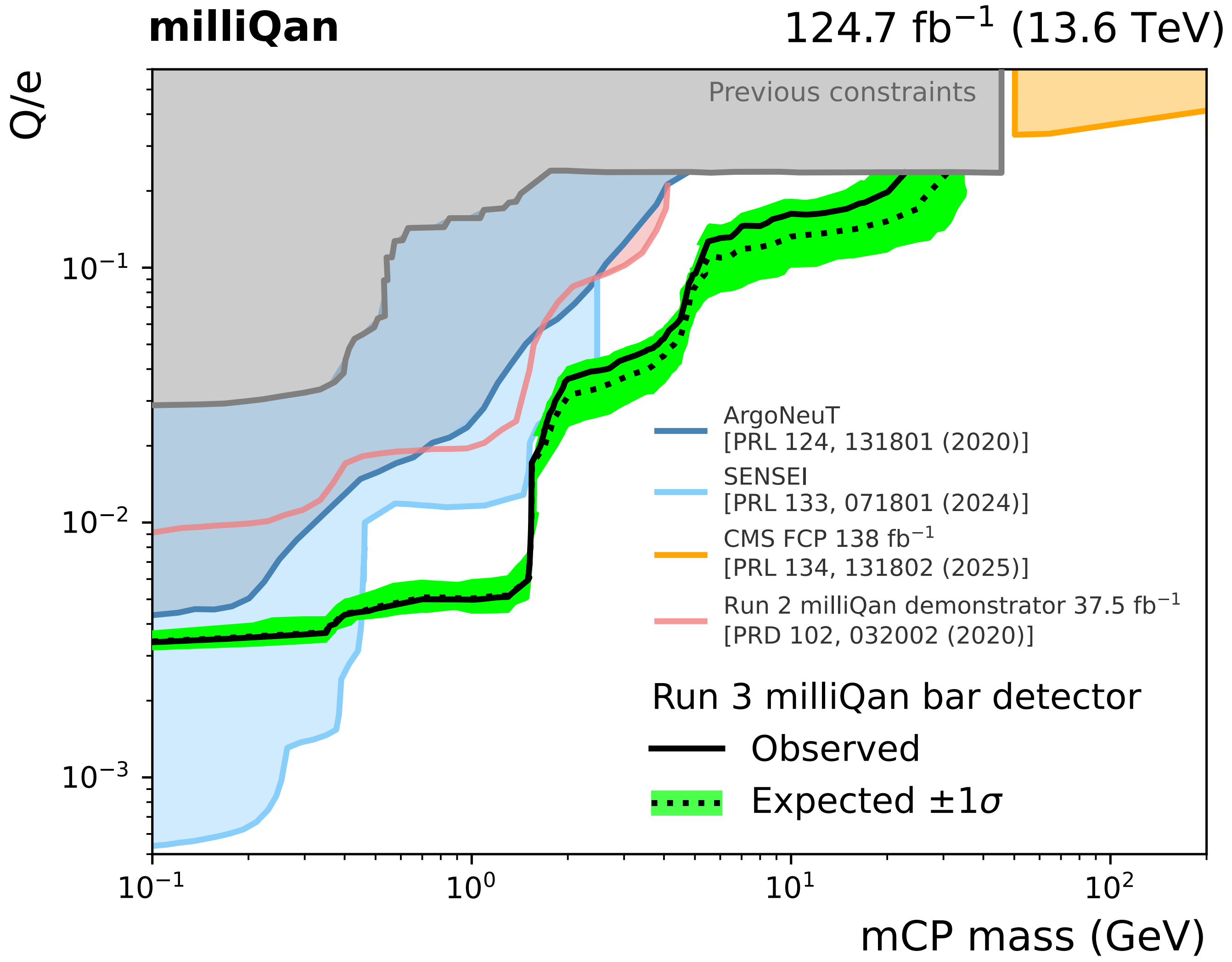
Search results!

- Results significantly extend constraints in charge/mass plane
- World leading limits on mCPs with masses 0.5 - 25 GeV!
- This despite only 40% of full Run 3 dataset analyzed (and only using data collected with bar detector)



Paper available at https://arxiv.org/abs/2506.02251 !

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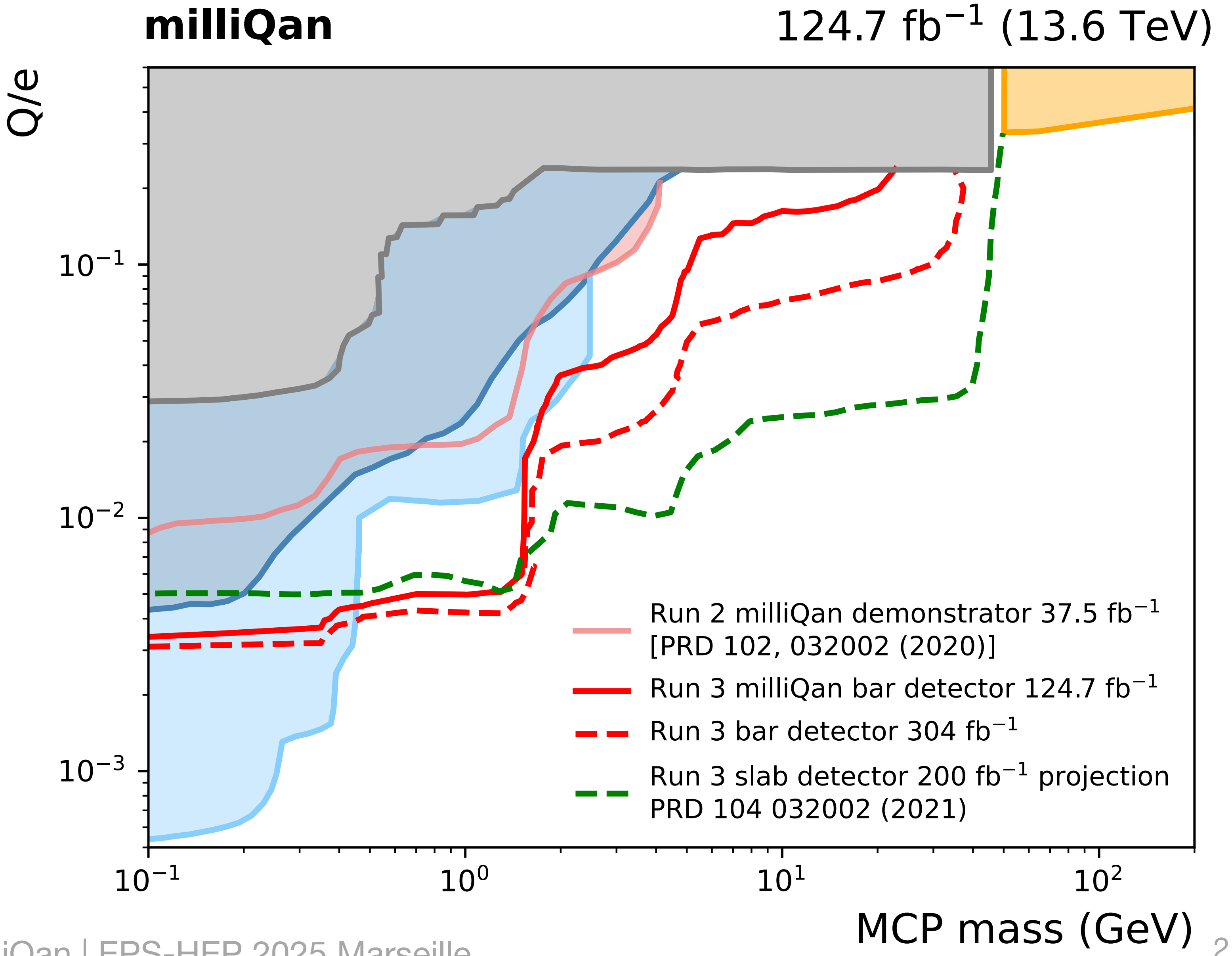
Expectation for full Run 3

- Adding 2025+2026 data gives significant **guaranteed** extension in reach with bar detector
    - Addition of hermetic front panel will reduce background << 1 for SR2
- Search already designed, will allow rapid top up
- Slab detector is online for 2025 running will extend even further!



Summary & Outlook

- milliQan has searched for millicharged particles using 124.7 fb^{-1} pp collision data at $\sqrt{s}$ = 13.6 TeV collected by its bar detector in 2023-24
- No candidate mCP events were observed and we have set world leading constrains on millicharged particles with masses 0.5 - 25 GeV.
- We look forward to exploring the remainder of the significant accessible parameter space with the addition of 2025-26 Run 3 data that will include our slab detector

For more information and a general overview of the experiment, check out this short film about milliQan produced for the recent 2025 APS global physics summit:

https://www.youtube.com/watch?v=rFjgGTclM9E

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The milliQan collaboration

THE OHIO STATE UNIVERSITY

CERN

VUB

University of BRISTOL

BOSTON UNIVERSITY

NYU

الجامعة اللبنانية
UNIVERSITE LIBANAISE

This speaker supported by funding from DOE Office of Science

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End

Backup

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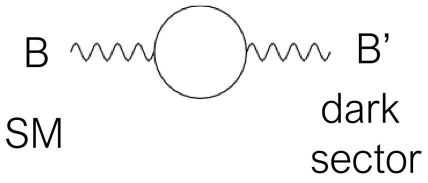
Why millicharged particles?

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

$$\mathcal{L}_{\text{dark-sector}} = -\frac{1}{4}A'_{\mu\nu}A'^{\mu\nu} + i\bar{\psi}'(\gamma^\mu\partial_\mu + ie'\gamma^\mu A'_\mu + iM_{\text{mCP}})\psi' - \frac{\kappa}{2}A'_{\mu\nu}B^{\mu\nu}$$

massless “dark photon” — “dark fermion” with mass M_{mCP}, charge e' — 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 $A'_\mu \rightarrow A'_\mu + \kappa B_\mu$ 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**

see e.g. ***arXiv:2104.07151v2*** for more details

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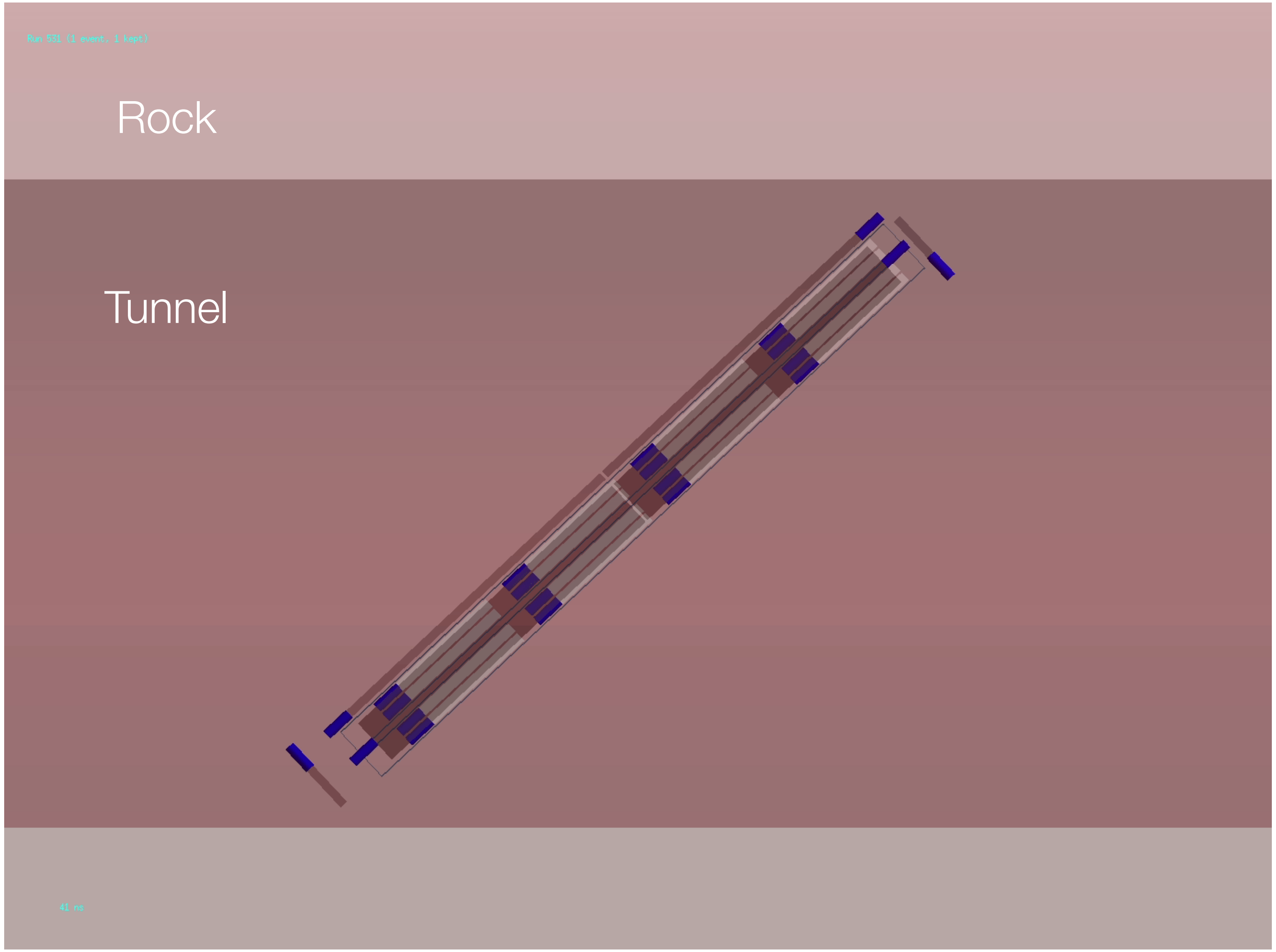
Millicharged particle through detector



$Q_{\mathrm{mCP}} = 0.01e$

Legend:

μ, γ, mCP, e^{-},
optical photon

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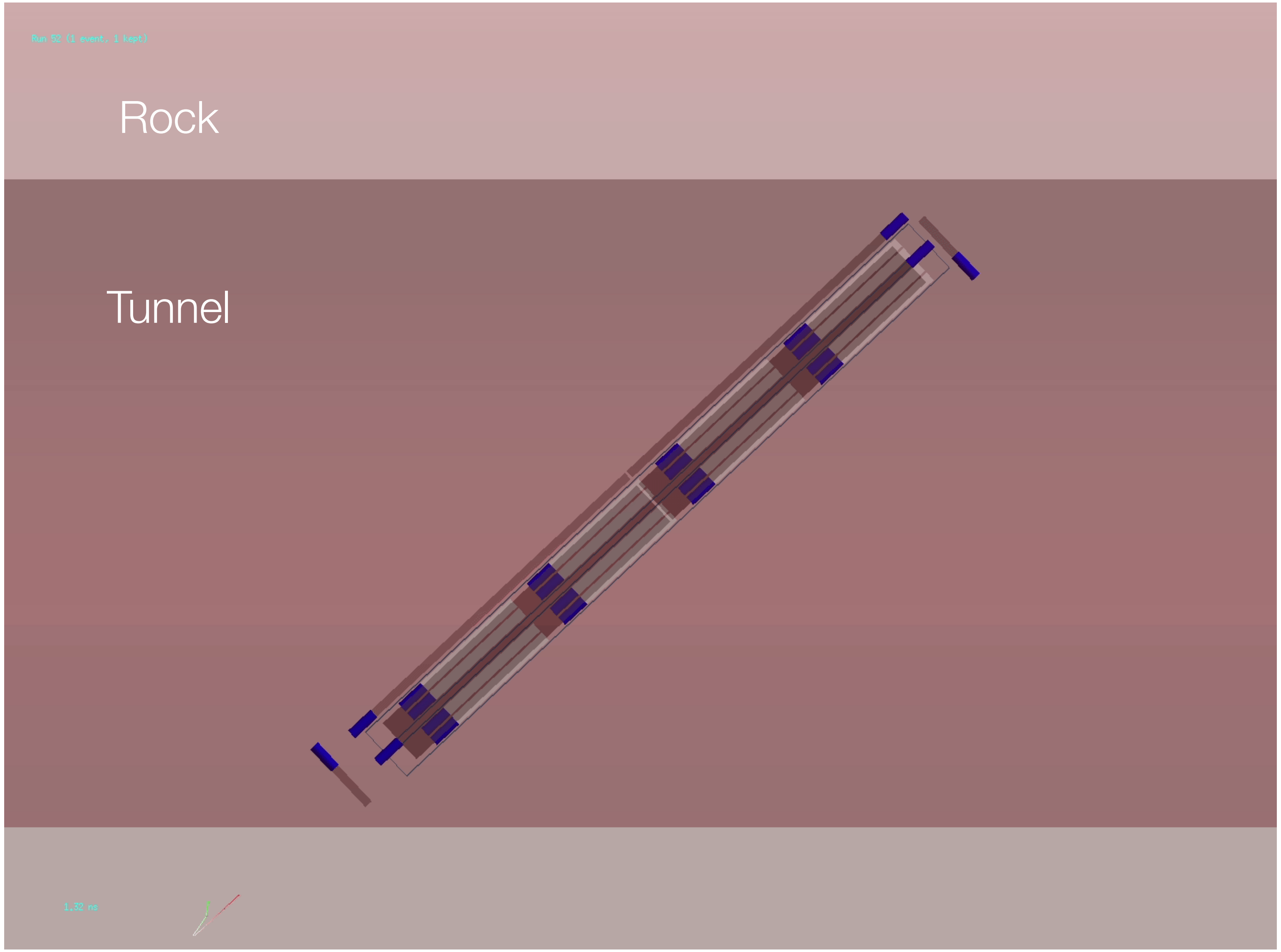
Through going muons



- Muons from CMS I.P. go through all 4 layers
- Useful for alignment and calibration
- Deposits large signal in bars and show-up in front+back panels

Legend:
μ, γ, mCP, e^-,
optical photon

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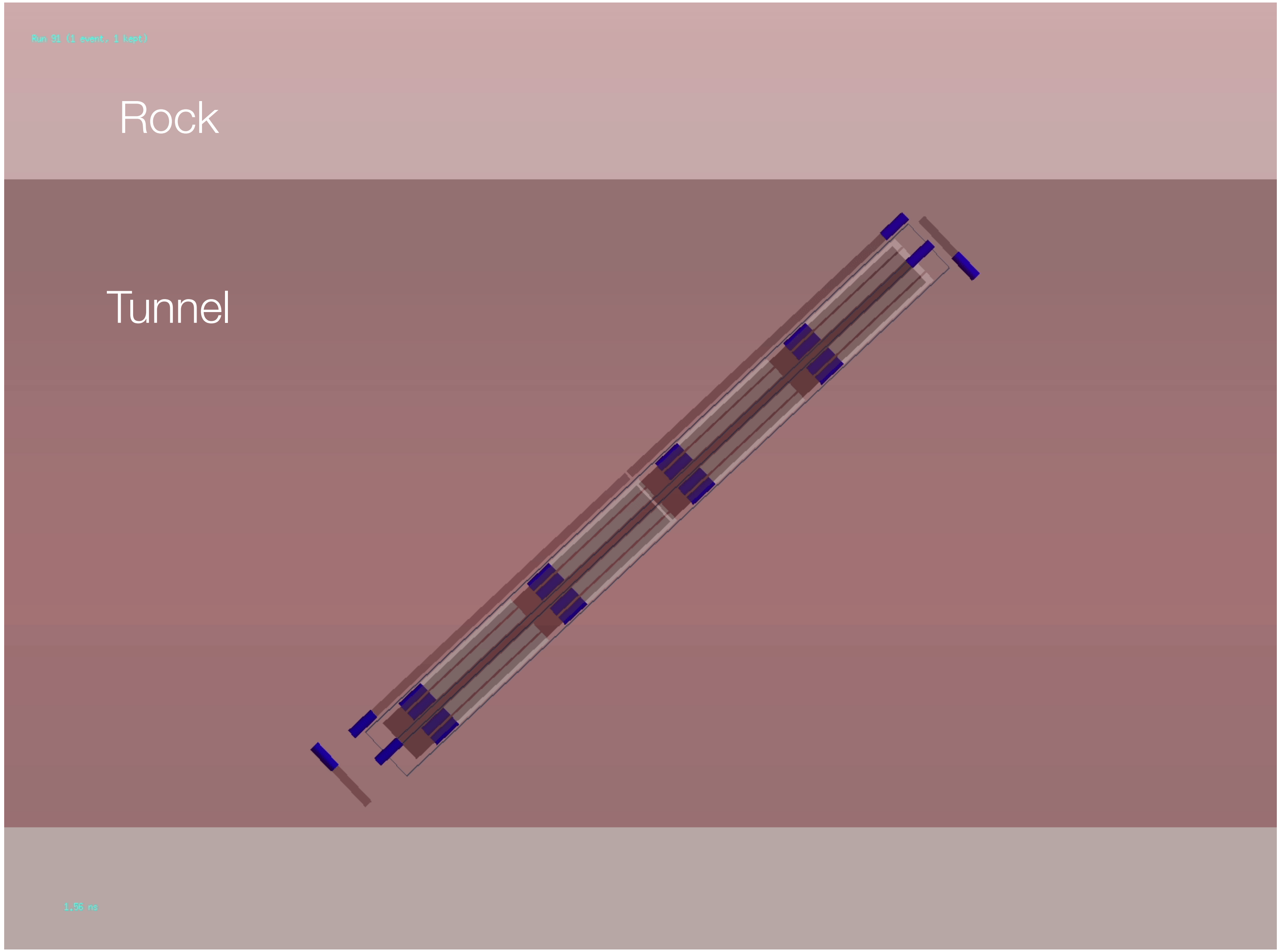
Background from cosmic ray showers



- With quad coincidence, random backgrounds are negligible
- Dominant remaining background from cosmic ray showers
  - Correlated hits between layers
- Veto by thin scintillator panels surrounding detector

Legend:
μ, γ, mCP, e^-,
optical photon

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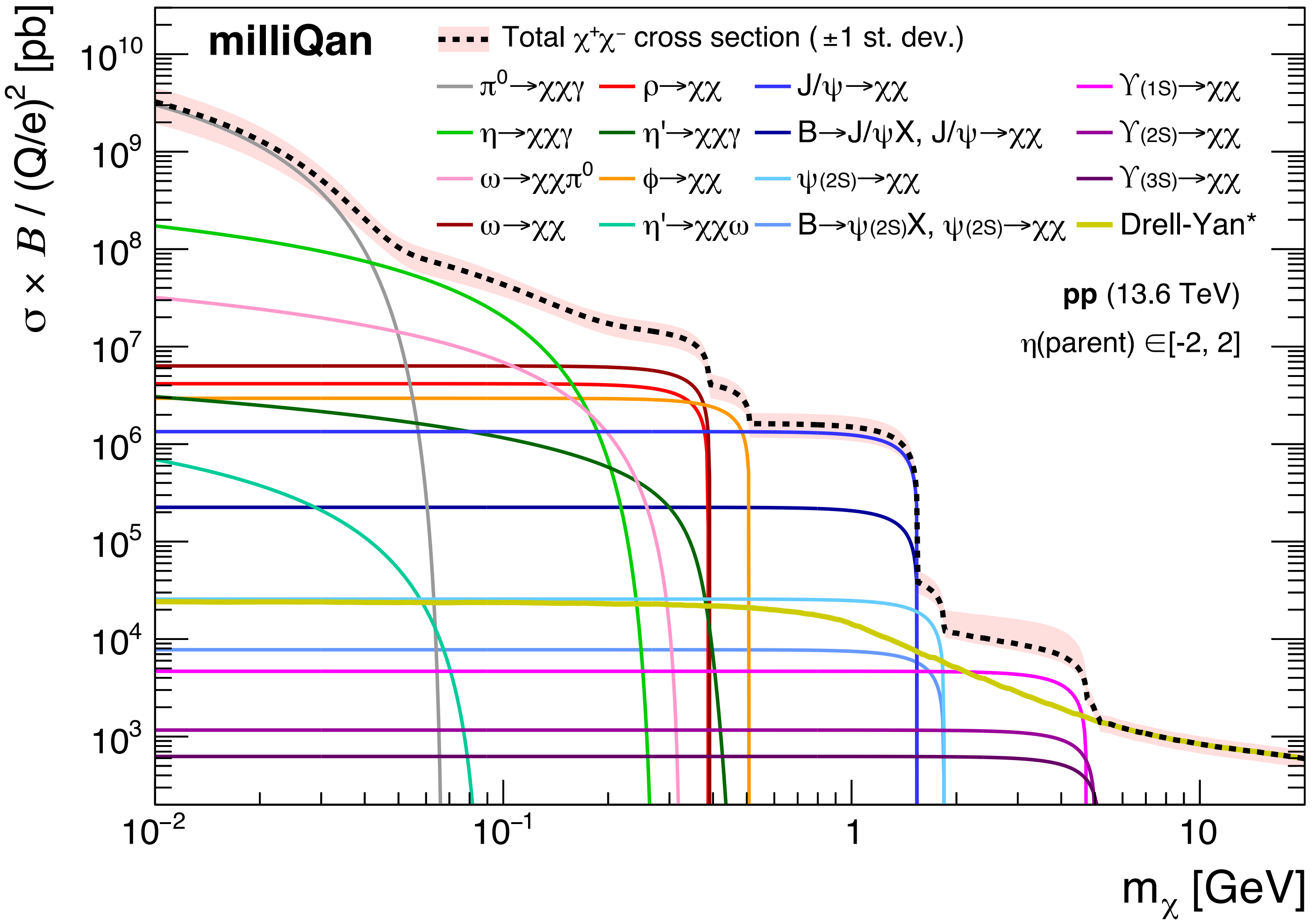
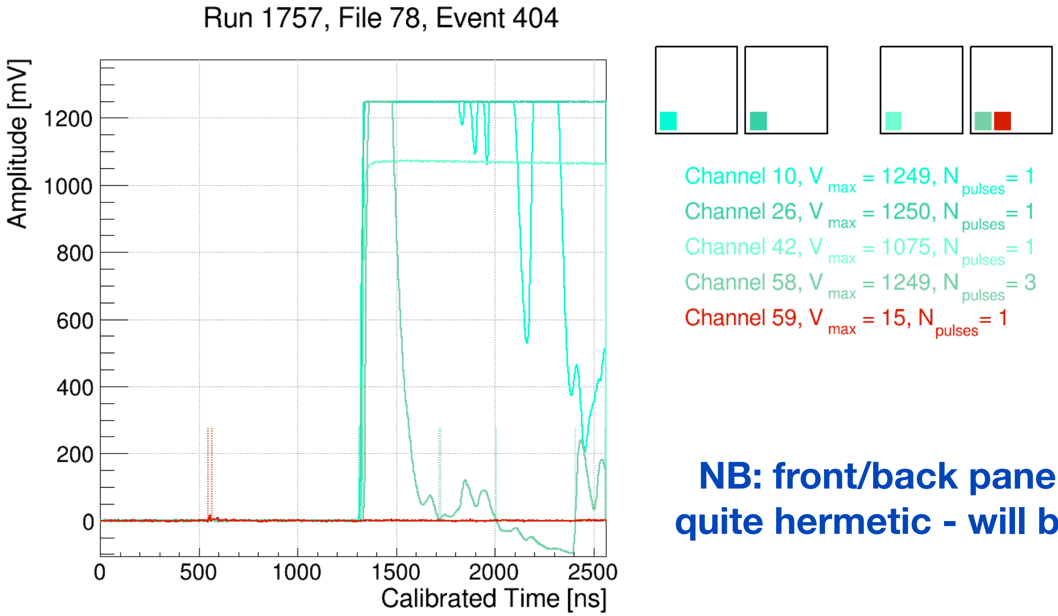
Signal simulation



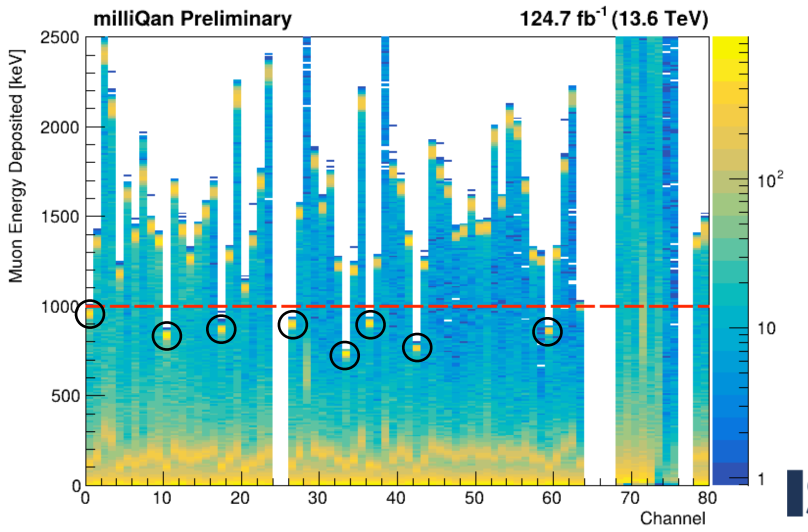
Signal simulation comprised of a wide range of DY/meson producction channels

Muon event that initially leaked into SR1

- Event displays clearly indicate the observed event is a muon that evaded veto
- Due to 8 out of 80 channels saturating at lower than nominal energy (black circles)
    - Energy deposited by a muon in such a channel thus below veto threshold (red line)
    - Somewhat improbably, this turned out to be the case for 3/4 channels hit by the muon in this event!
- Addressed by lowering the muon veto threshold for these channels and re-running analysis



NB: front/back panels not quite hermetic - will be fixed



For full transparency, we document this as a **post-unblinding fix**

Cutflow for SR1 & SR2

Selection Criteria	Signal Region 1			Signal Region 2		
	Data Beam-On t=3393 h	Signal MC m=0.1 GeV Q/e=0.004	Signal m=1.0 GeV Q/e=0.008	Data Beam-On t=3393 h	Signal m=1.7 GeV Q/e=0.03	Signal m=10.0 GeV Q/e=0.2
Triggered Events	26864552	324.0	61.3	26864552	27.0	37.2
Cosmic Muon Veto	790776	324.0	61.3	790776	27.0	37.2
Pulse/Event Quality	506417	323.9	61.3	790383	27.0	37.2
Shower Veto	3369	12.0	19.3	9152	7.7	9.5
SR1: $\leq$ 4 Bars	985	11.7	19.3	—	—	—
Noise Filter	985	11.7	19.3	9113	7.7	9.5
Energy Max/Min	336	10.3	16.5	1827	7.6	9.5
SR1: Beam Muon Veto	331	10.3	16.5	—	—	—
SR1: End Panel Veto	209	10.1	14.3	—	—	—
Straight Line	3	9.2	14.3	1372	7.5	9.4
Δ T(max-min) $\leq$ 20 ns	0	8.7	14.1	1355	7.5	8.6
SR2: End Panel Required	—	—	—	1320	5.8	8.2
SR2: $\leq$ 4 Bars	—	—	—	84	5.8	7.3
SR2: $nPE^{Panel}_{max} < 70$	—	—	—	2	5.8	7.0

TABLE I. Sequential impact of selection criteria on the number of events in the mCP search. Criteria in same row can differ between SR1 and SR2 as detailed in text. Bold type indicates criteria that are applied only to SR1 or SR2.

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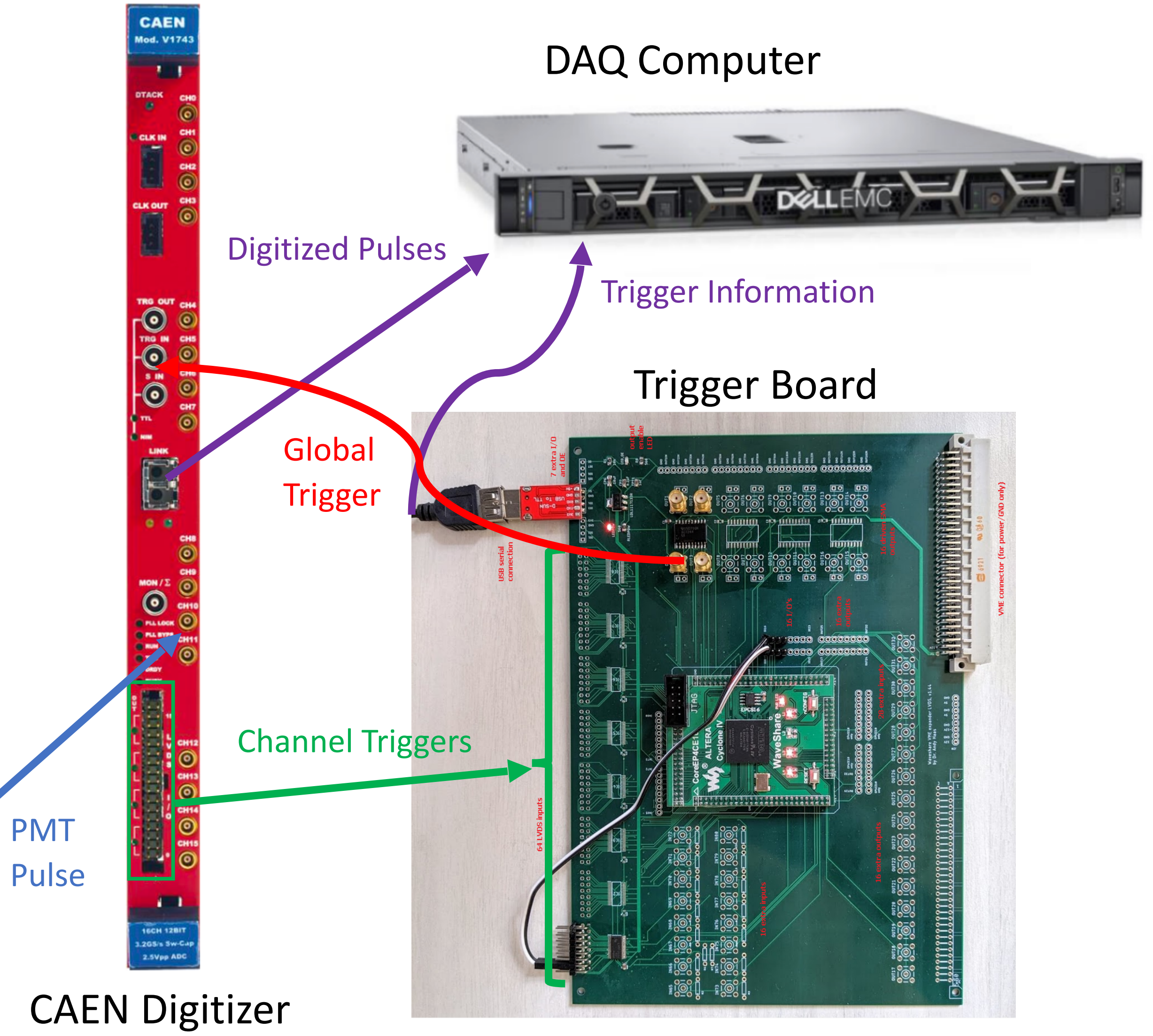
Trigger and DAQ

- Uses new “trigger board” to trigger the detectors
- PMT data input to CAEN digitizer
- Digitizers send triggers from PMTs to trigger board
- Trigger board logic determines if board should fire
- Uses FPGA to program our trigger menu



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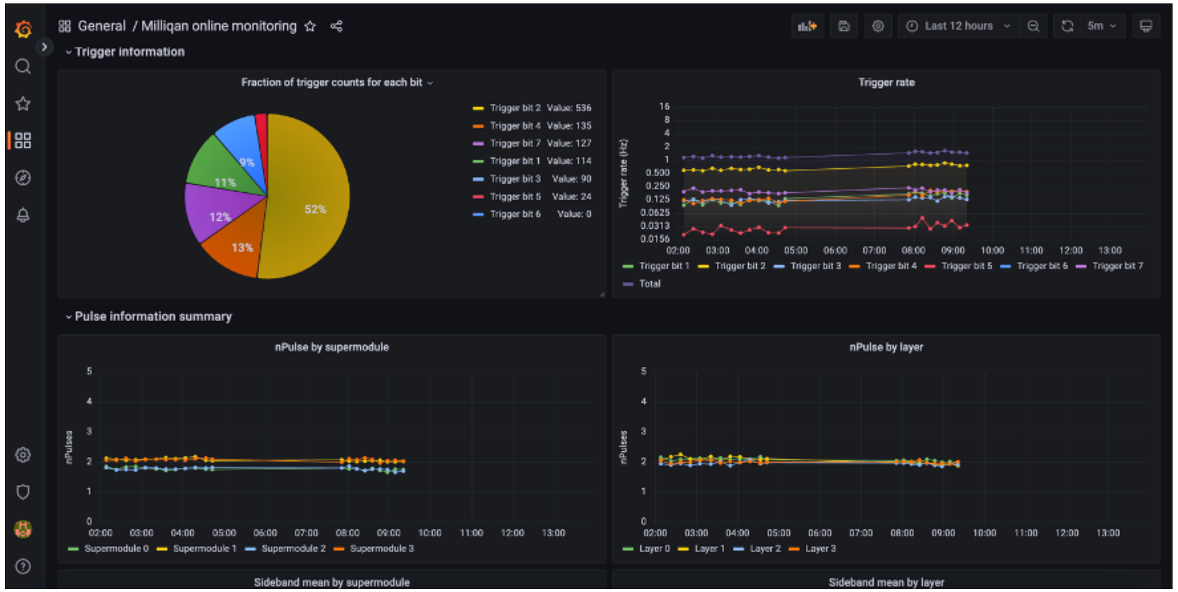
DAQ & Trigger Monitoring

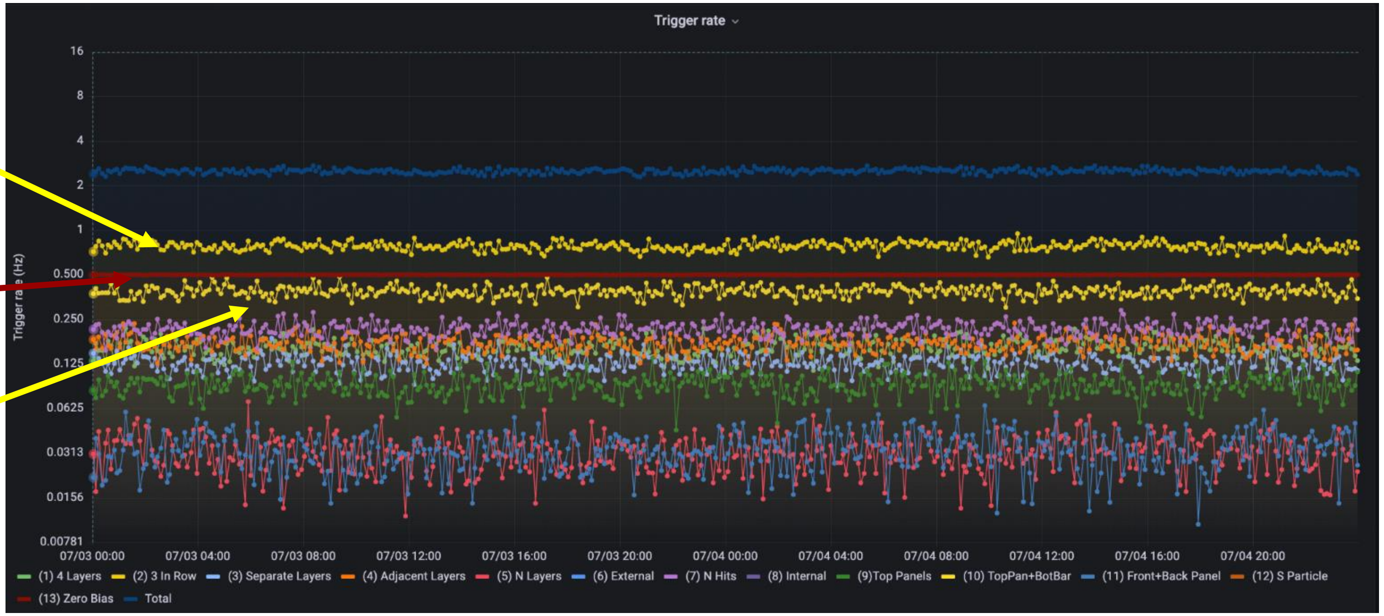
- Web-based interfaces/DBs to run & monitor the detector
  - Stable continuous data taking since June 1st 2023



dominant trigger still 3 in a row

zero bias 0.5Hz

cosmics top+bot



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