Searching for millicharged particles at the LHC (and beyond)

2025.10.13

Juan Salvador Tafoya Vargas (UC Davis)
on behalf of the milliQan and FORMOSA collaborations

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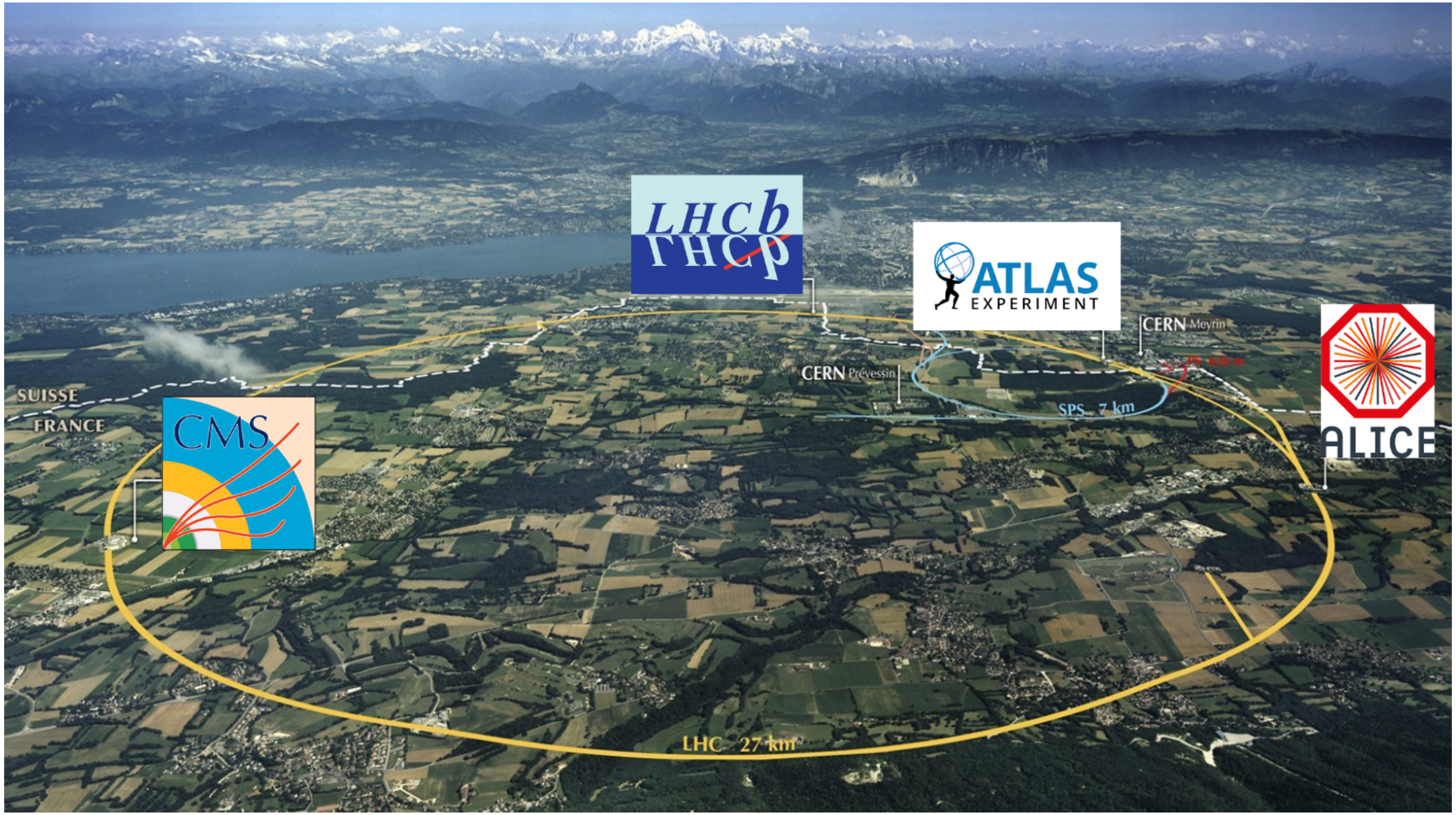
New physics and dark matter

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

What if new physics simply doesn't interact with SM matter?



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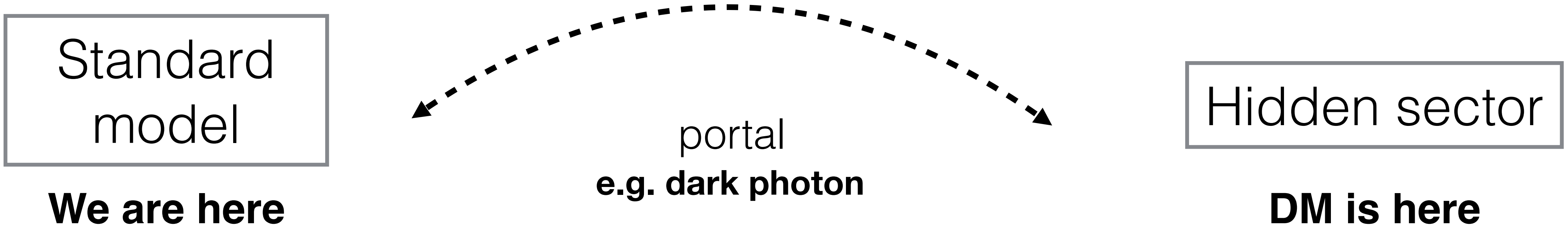
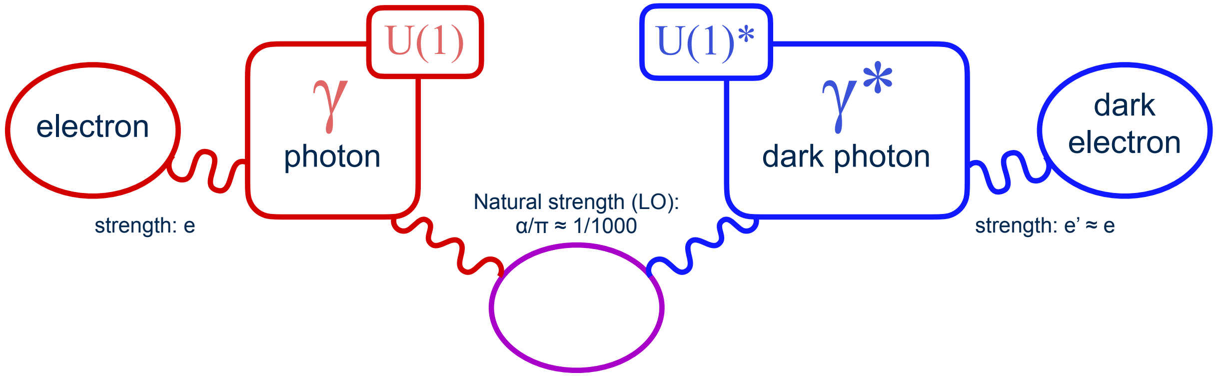
What if DM has no SM interaction?



- Intriguing possibility: dark matter could be part of a **“hidden” universe with no SM gauge interactions**
- Hidden universe can have **complex structure** and provide solutions to mysteries beyond DM
- Must be some communication between sectors via a “portal”

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

→

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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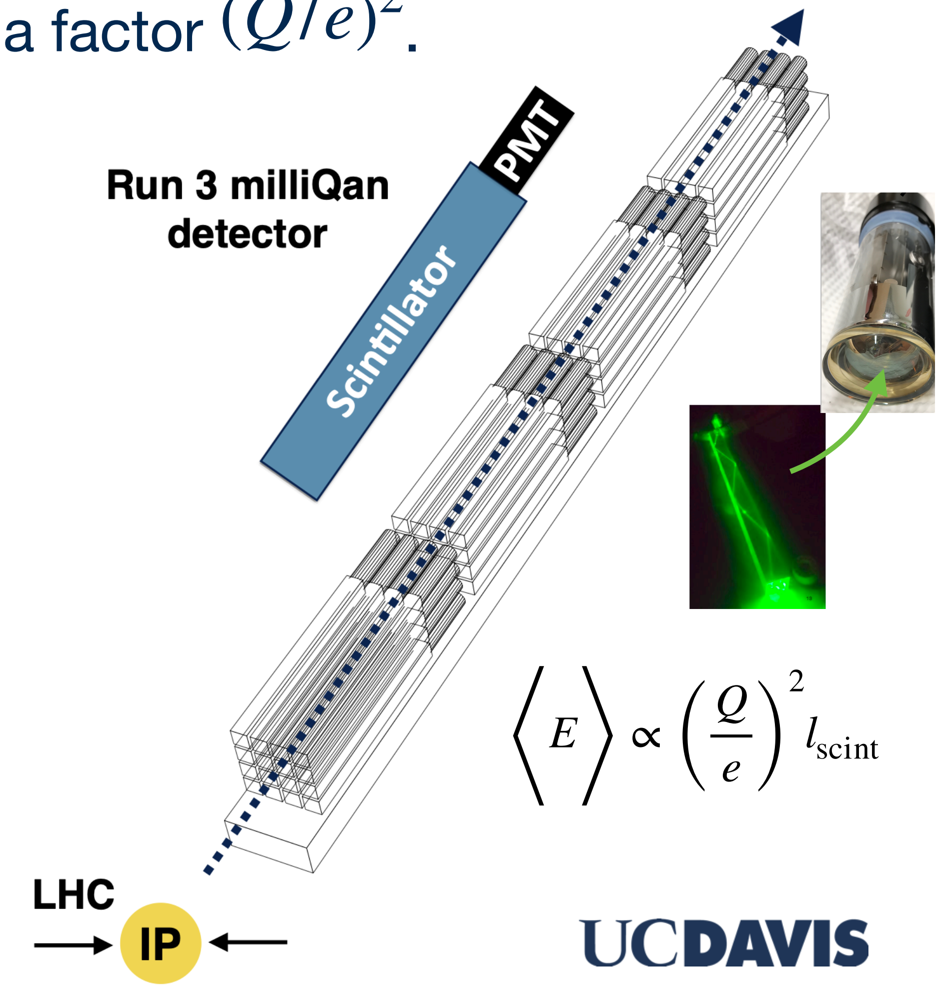
Millicharged particle searches at the LHC

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

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)

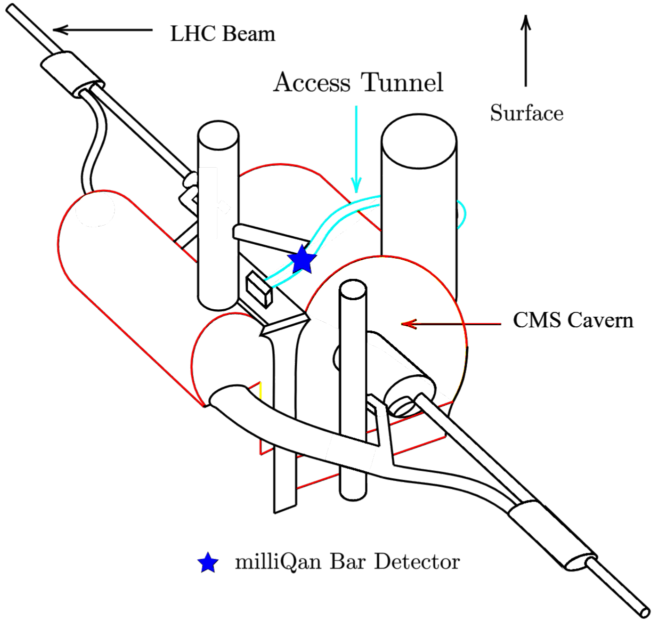


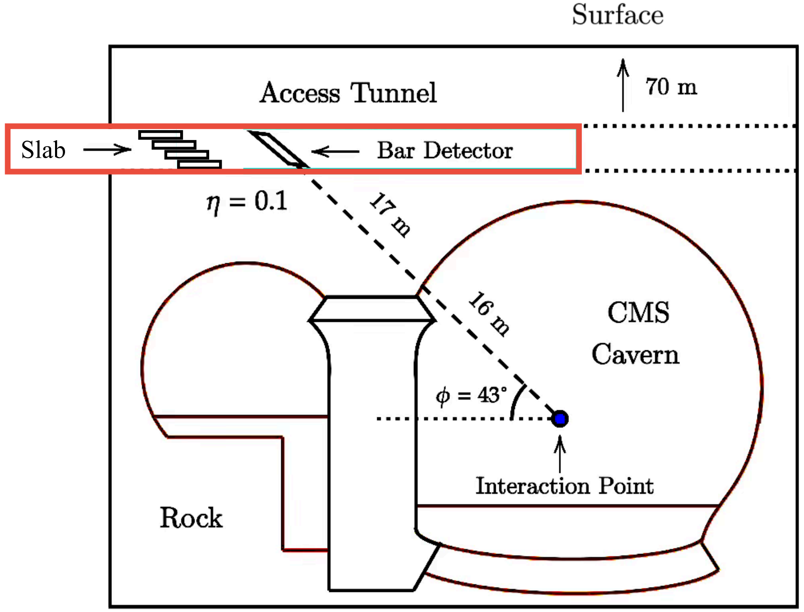
$$\langle E \rangle \propto \left(\frac{Q}{e}\right)^2 l_{\text{scint}}$$

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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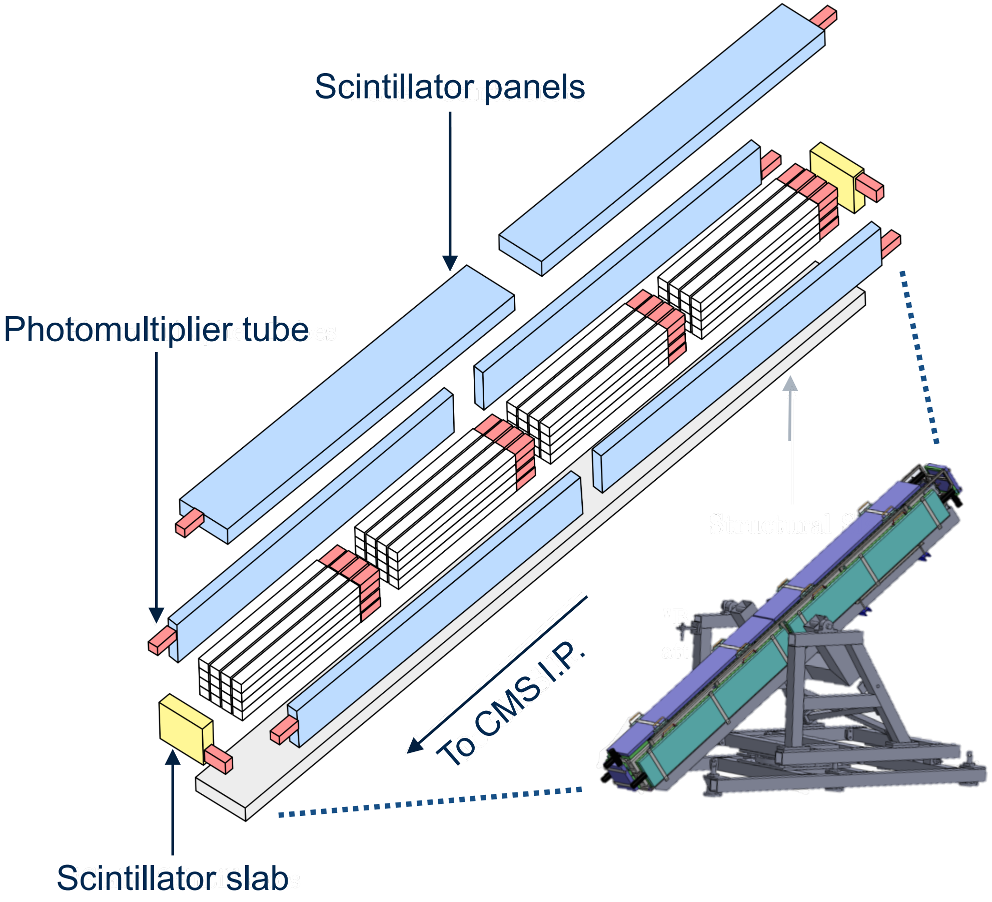
Run 3 bar detector

- Installed in early 2023
- Array of four layers of 4x4 60x5x5cm EJ-200 scintillator bars
- Bars coupled to Hamamatsu R878 PMTs (amplified to allow sPE sensitivity)
- Veto panels to provide active rejection of cosmic and beam muon deposits
- DAQ uses CAEN V1743 digitizers, readout by custom FPGA-based trigger board



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Bar detector completed in spring 2023

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

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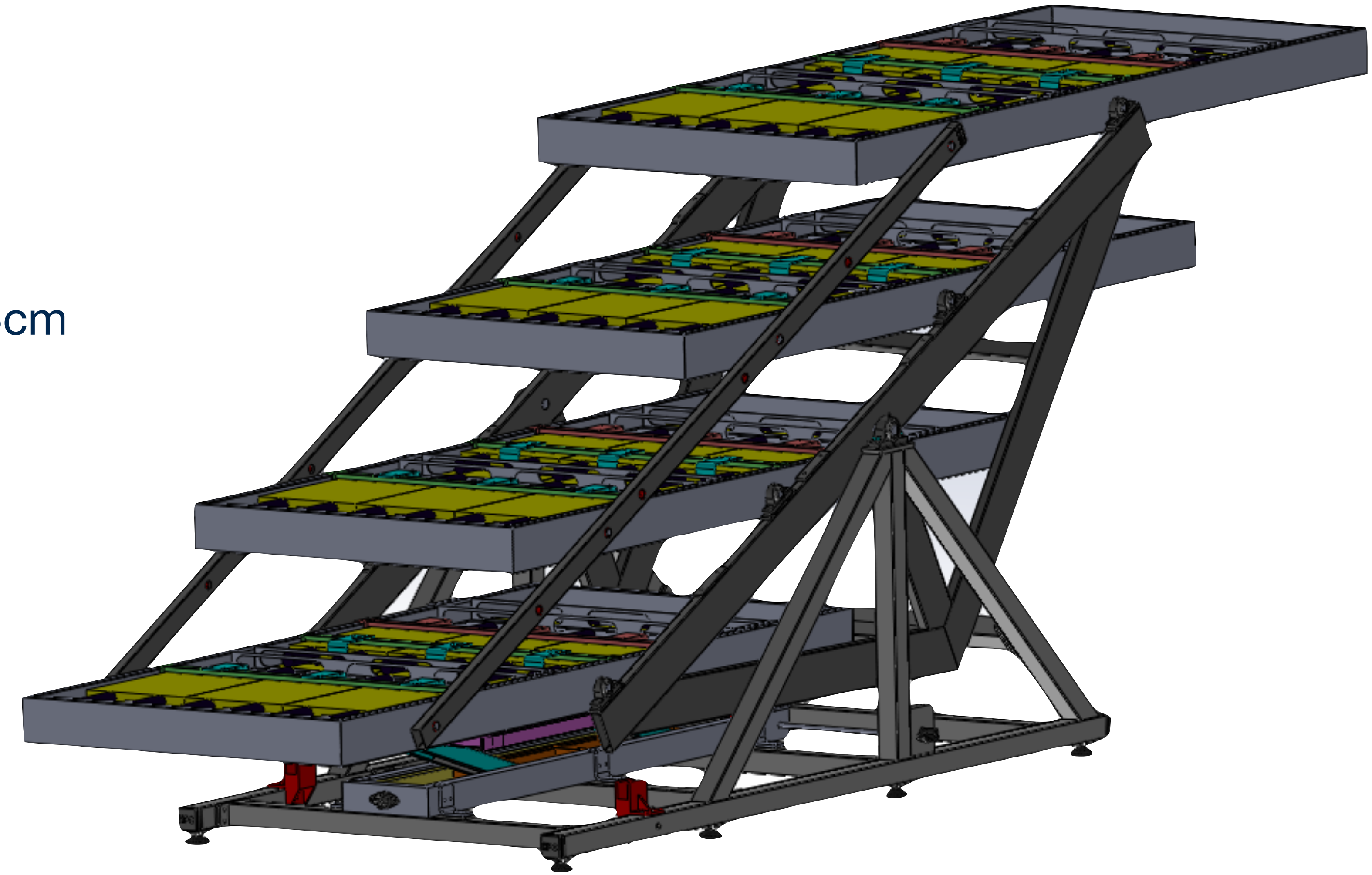
Run 3 slab detector



- Four layers of twelve 40x60x5cm scintillator slabs
- Surface equivalent to the coverage of **~1000 bars**
- Similarly to bar, readout by Hamamatsu R878 PMTs
- Target: significantly improve acceptance for $Q > \sim 0.01e$

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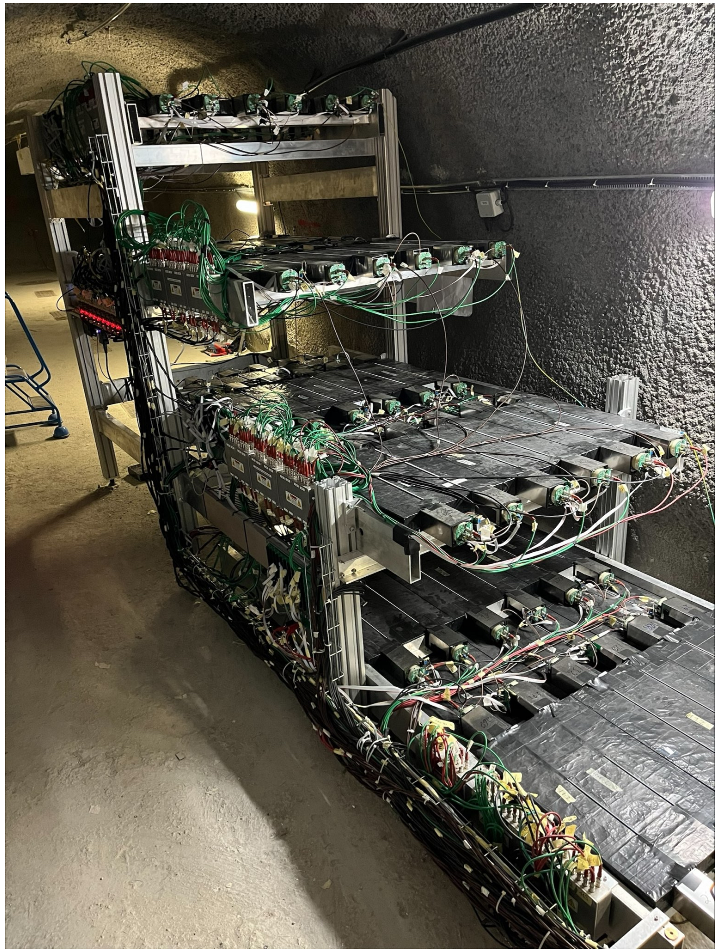
Slab detector completed in summer 2024



- Smoothly taking data since October 2024
- Fully commissioned now, collecting physics-quality data

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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
- Run 3 detector is sensitive to significant region of unexplored parameter space

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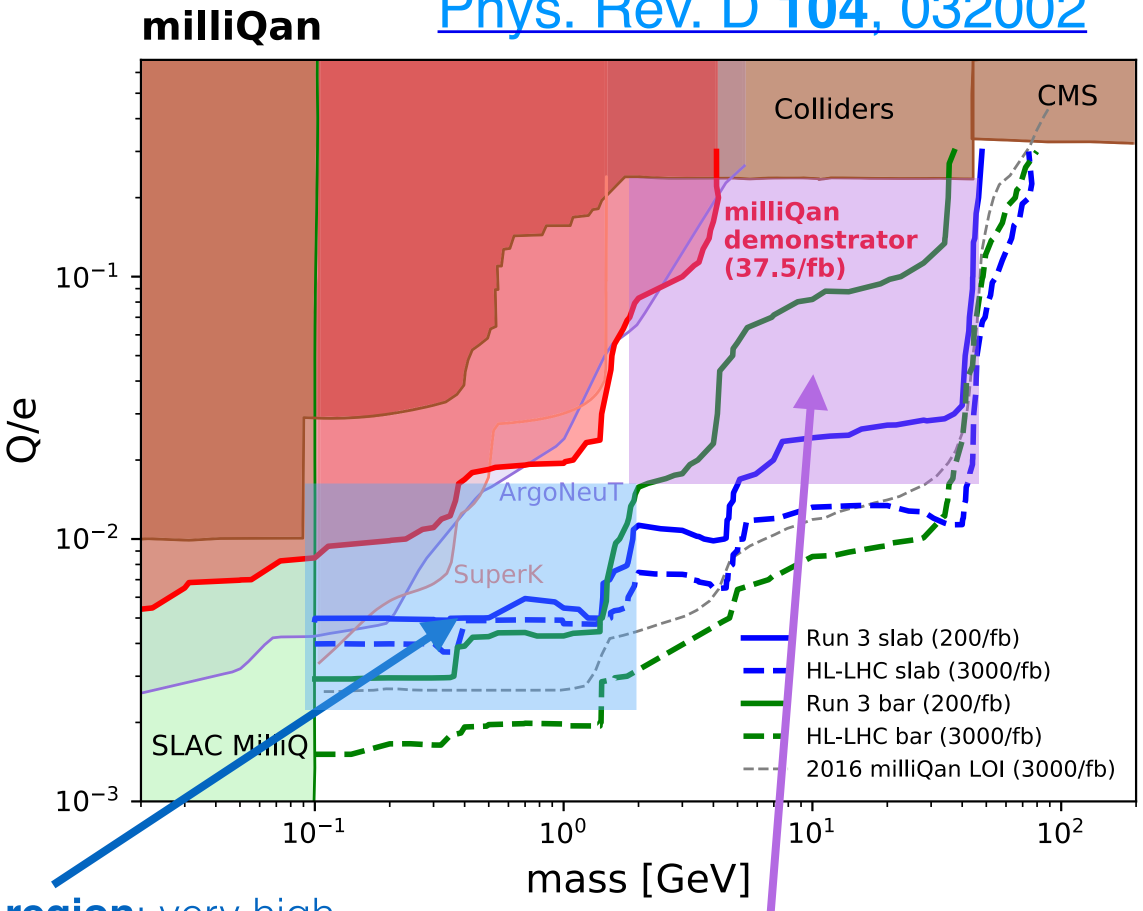

Charge limited region: very high mCP flux but low efficiency (*long bars*)

Acceptance limited region: high efficiency but mCP flux is low (wide s*labs*)

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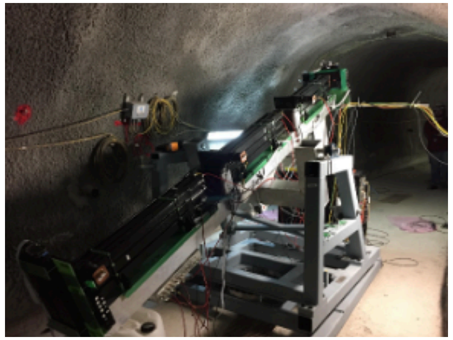
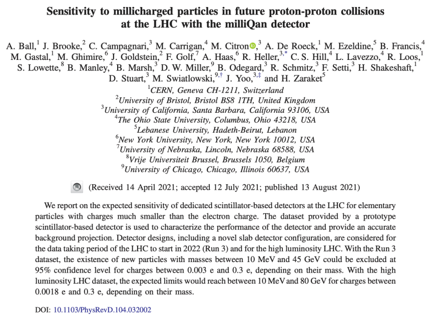
Summary of timeline



milliQan demonstrator commissioned (June 2018)



Sensitivity to millicharged particles in future proton-proton collisions at the LHC with the milliQan detector

A. Ball,[1] J. Brooke,[2] C. Campagnari,[3] M. Carrigan,[4] M. Citron,[3] A. De Roeck,[1] M. Ezeldine,[5] B. Francis,[4] M. Gastal,[1] M. Ghimire,[6] J. Goldstein,[2] F. Golf,[7] A. Haas,[6] R. Heller,[3,*] C. S. Hill,[4] L. Lavezzo,[4] R. Loos,[1] S. Lowette,[8] B. Manley,[4] B. Marsh,[3] D. W. Miller,[9] B. Odegard,[3] R. Schmitz,[3] F. Setti,[3] H. Shakeshaft,[1] D. Stuart,[3] M. Swiatlowski,[9,†] J. Yoo,[3,‡] and H. Zaraket[5]

[1]*CERN, Geneva CH-1211, Switzerland*
[2]*University of Bristol, Bristol BS8 1TH, United Kingdom*
[3]*University of California, Santa Barbara, California 93106, USA*
[4]*The Ohio State University, Columbus, Ohio 43218, USA*
[5]*Lebanese University, Hadeth-Beirut, Lebanon*
[6]*New York University, New York, New York 10012, USA*
[7]*University of Nebraska, Lincoln, Nebraska 68588, USA*
[8]*Vrije Universiteit Brussel, Brussels 1050, Belgium*
[9]*University of Chicago, Chicago, Illinois 60637, USA*

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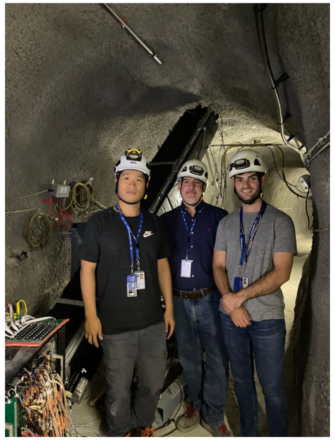
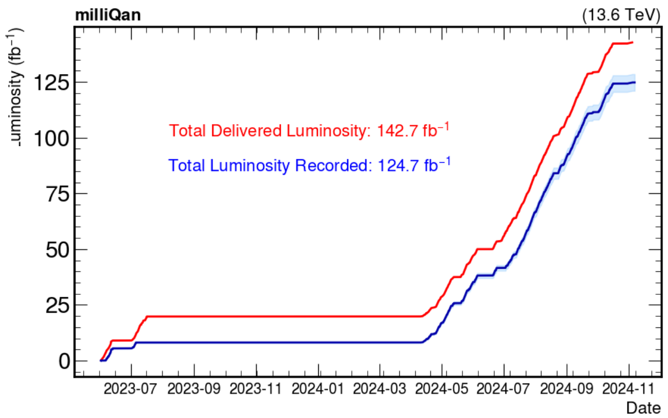
We report on the expected sensitivity of dedicated scintillator-based detectors at the LHC for elementary particles with charges much smaller than the electron charge. The dataset provided by a prototype scintillator-based detector is used to characterize the performance of the detector and provide an accurate background projection. Detector designs, including a novel slab detector configuration, are considered for the data taking period of the LHC to start in 2022 (Run 3) and for the high luminosity LHC. With the Run 3 dataset, the existence of new particles with masses between 10 MeV and 45 GeV could be excluded at 95% confidence level for charges between 0.003 e and 0.3 e, depending on their mass. With the high luminosity LHC dataset, the expected limits would reach between 10 MeV and 80 GeV for charges between 0.0018 e and 0.3 e, depending on their mass.

DOI: 10.1103/PhysRevD.104.032002

Run 3 projections paper (June 2023)

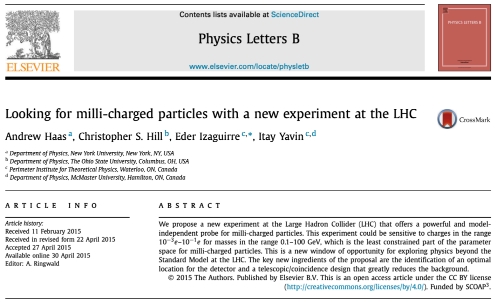


Bar detector commissioned (June 2023)



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

milliQan proposal (2014)



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Looking for milli-charged particles with a new experiment at the LHC

Andrew Haas[a], Christopher S. Hill[b], Eder Izaguirre[c,*], Itay Yavin[c,d]

[a] *Department of Physics, New York University, New York, NY, USA*
[b] *Department of Physics, The Ohio State University, Columbus, OH, USA*
[c] *Perimeter Institute for Theoretical Physics, Waterloo, ON, Canada*
[d] *Department of Physics, McMaster University, Hamilton, ON, Canada*

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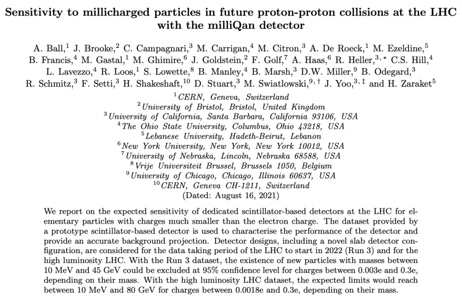
ABSTRACT

We propose a new experiment at the Large Hadron Collider (LHC) that offers a powerful and model-independent probe for milli-charged particles. This experiment could be sensitive to charges in the range $10^{-3}e$–$10^{-1}e$ for masses in the range 0.1–100 GeV, which is the least constrained part of the parameter space for milli-charged particles. This is a new window of opportunity for exploring physics beyond the Standard Model at the LHC. The key new ingredients of the proposal are the identification of an optimal location for the detector and a telescopic/coincidence design that greatly reduces the background.

millliQan demonstrator paper (2022)



Sensitivity to millicharged particles in future proton-proton collisions at the LHC with the milliQan detector

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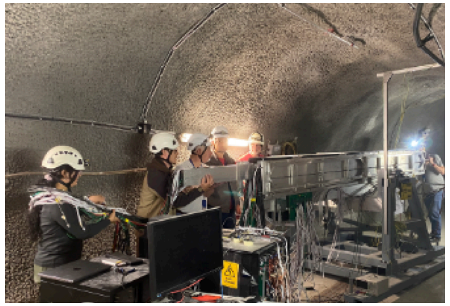
[8]*Vrije Universiteit Brussel, Brussels 1050, Belgium*
[9]*University of Chicago, Chicago, Illinois 60637, USA*
[10]*CERN, Geneva CH-1211, Switzerland*

(Dated: August 16, 2021)

We report on the expected sensitivity of dedicated scintillator-based detectors at the LHC for elementary particles with charges much smaller than the electron charge. The dataset provided by a prototype scintillator-based detector is used to characterise the performance of the detector and provide an accurate background projection. Detector designs, including a novel slab detector configuration, are considered for the data taking period of the LHC to start in 2022 (Run 3) and for the high luminosity LHC. With the Run 3 dataset, the existence of new particles with masses between 10 MeV and 45 GeV could be excluded at 95% confidence level for charges between 0.003e and 0.3e, depending on their mass. With the high luminosity LHC dataset, the expected limits would reach between 10 MeV and 80 GeV for charges between 0.0018e and 0.3e, depending on their mass.

Bar detector construction begins (2022)



Slab detector commissioned (July 2024)

Bar detector search (May 2025)

First Run 3 results!

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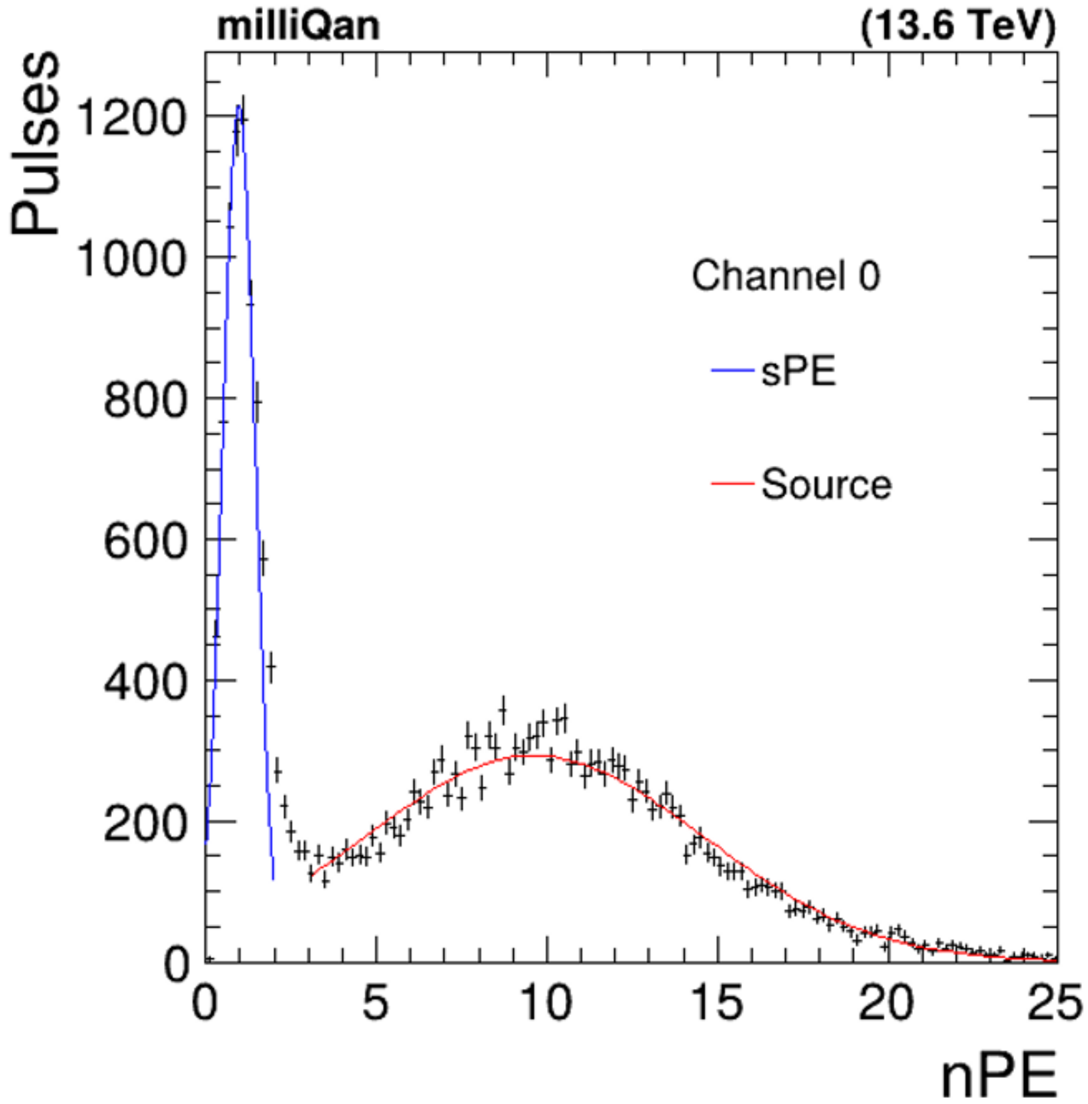
Energy calibrations

- PMT signal proprotional to N_{PE} (saturation at $10^{2-3}\ N_{PE}$)
- Measure response with $^{109}\mathrm{Cd}$ source (22 keV X-ray)
- Used to calibrate each channel in GEANT4 simulation to ensure correct response to mCP → accounts for differences in PMT quantum efficiency, bar wrapping, optical coupling etc…



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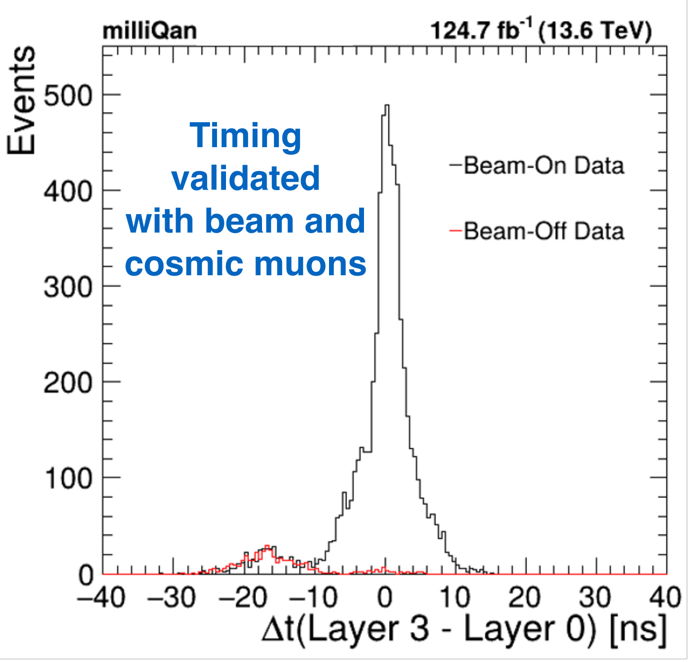
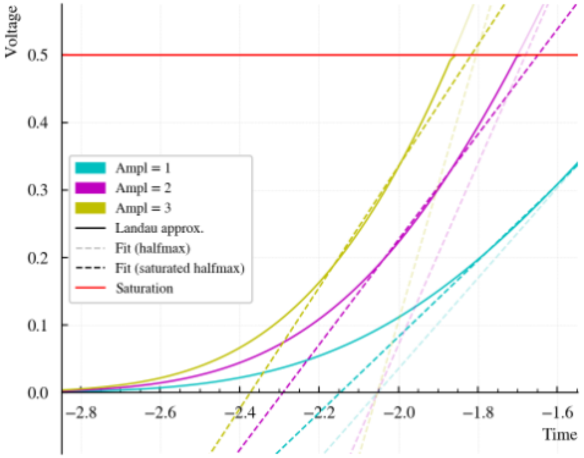
Timing calibrations

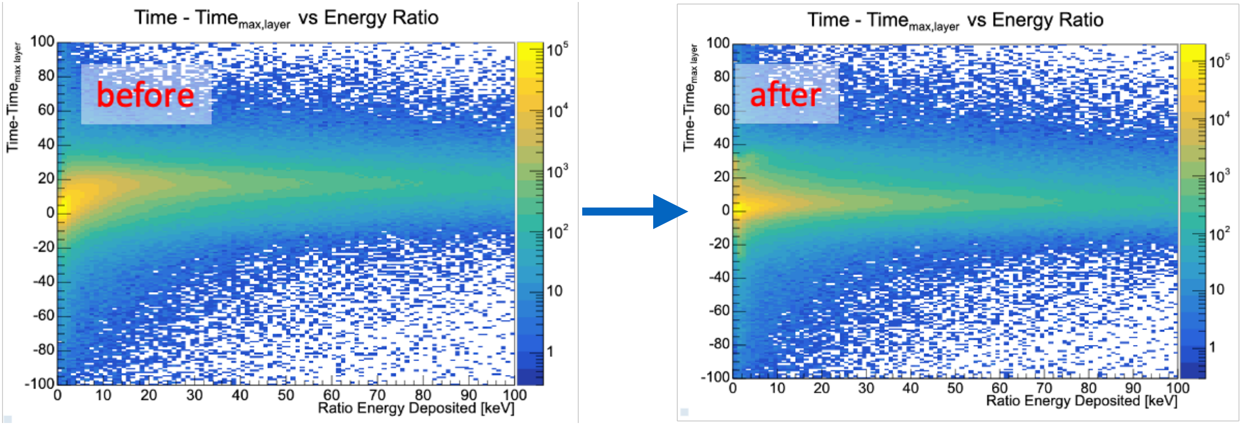


- Correct for timing shifts due to differences in electronics/cable lengths with beam on/off data + cosmic muons
- Calibrate such that particles traveling straight through detector from I.P. have same time in all channels
- Additional "timewalk"correction applied to ensure constant timing vs pulse area



Area of pulse impacts associated time

Timewalk correction



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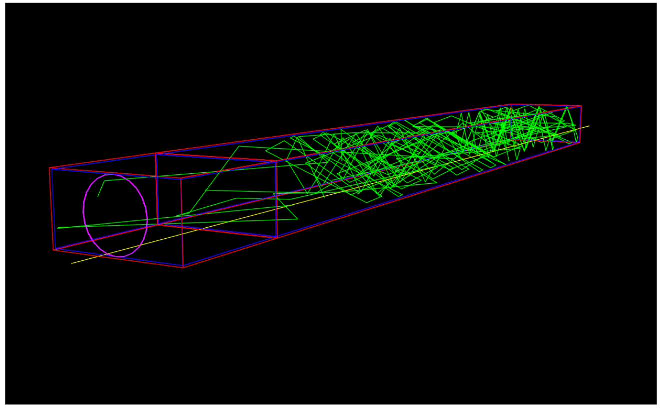
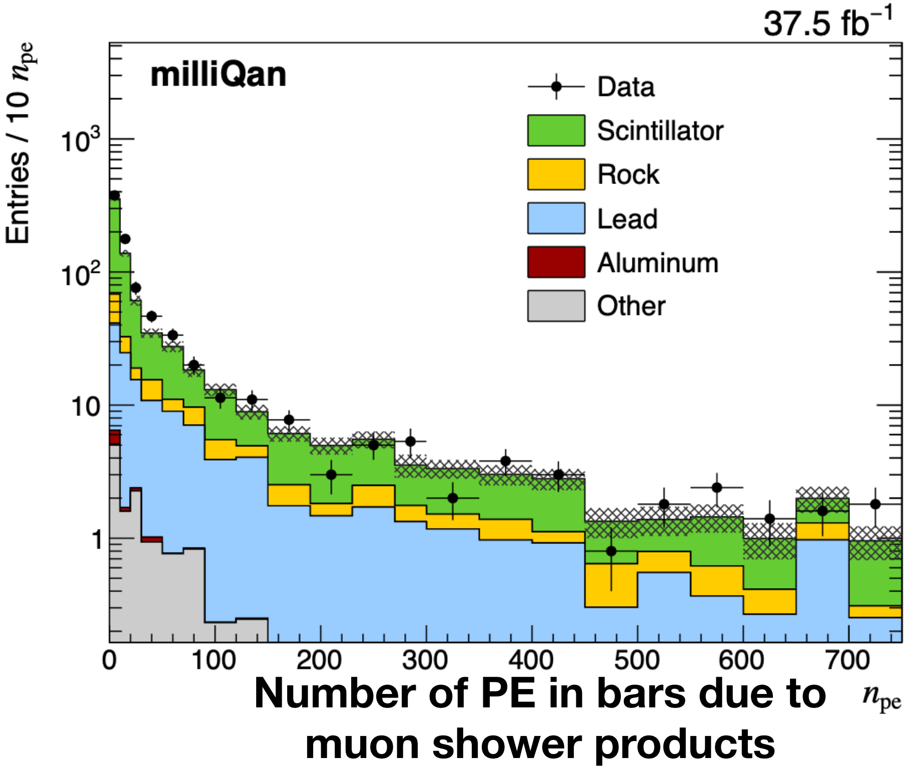
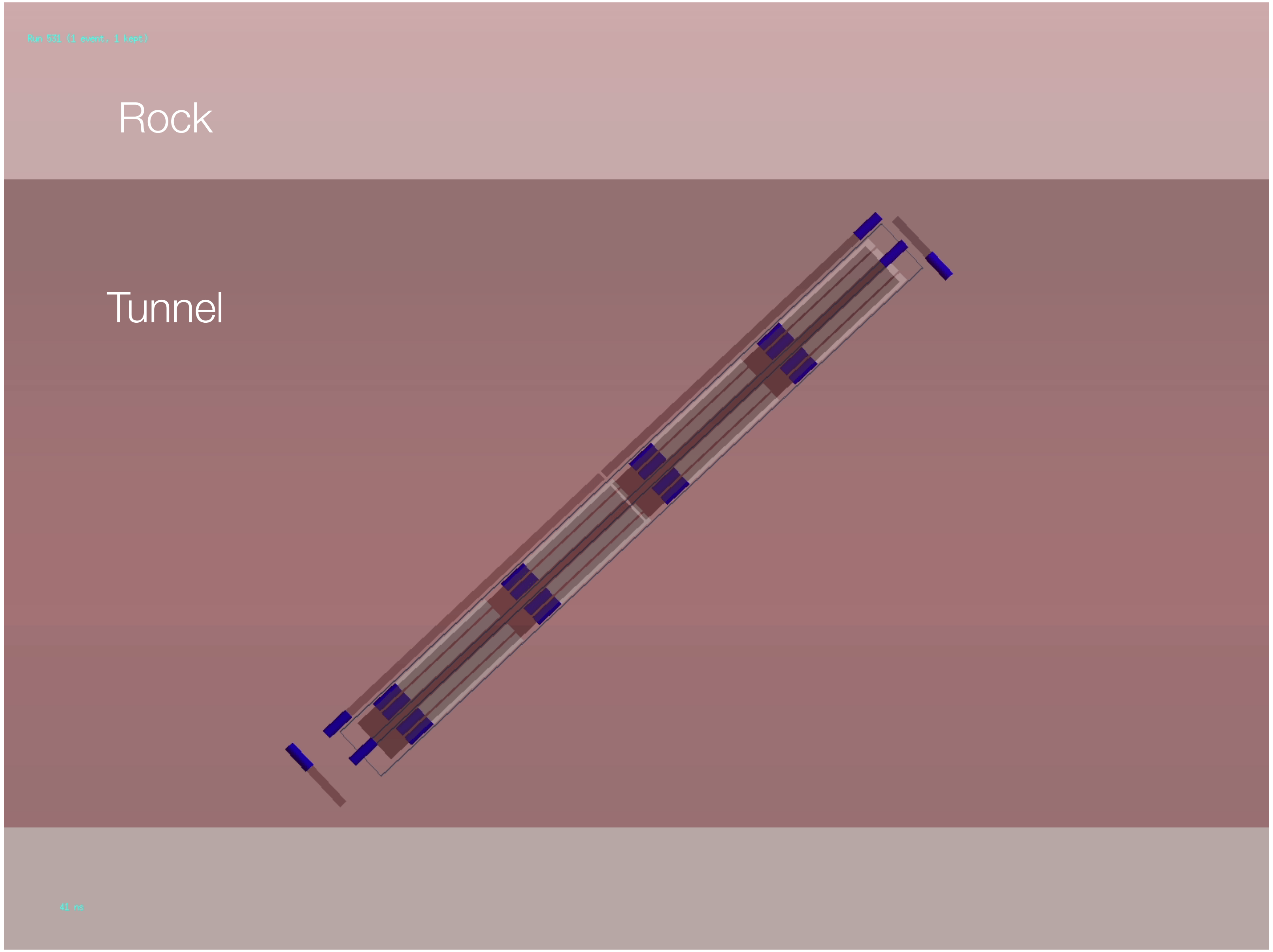
Detector simulation



- Full GEANT4 simulation of milliQan 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 and simulation calibrated
  → **search for millicharged particles!**



A fully calibrated GEANT simulation



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

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

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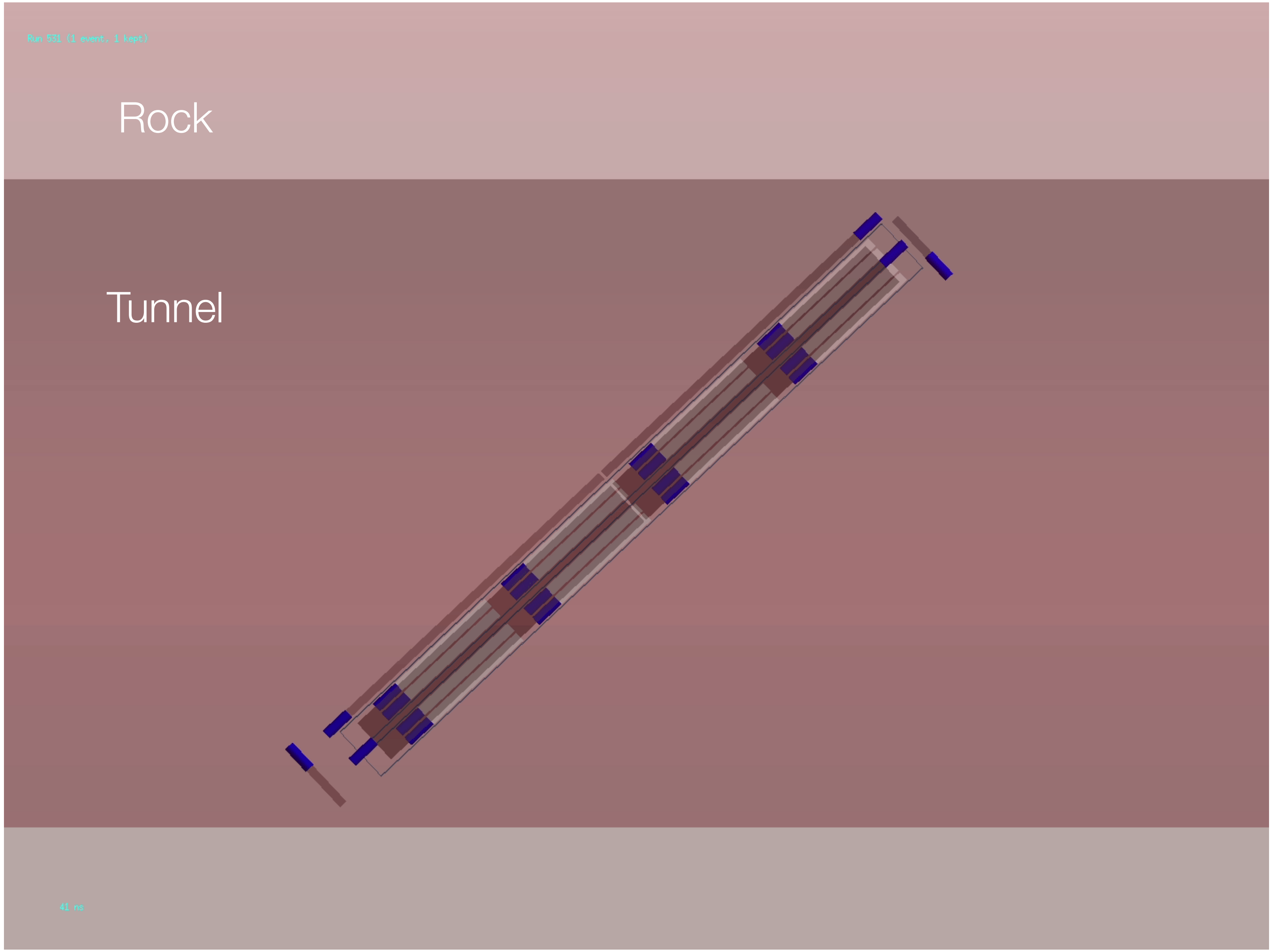
A fully calibrated GEANT simulation



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Legend:
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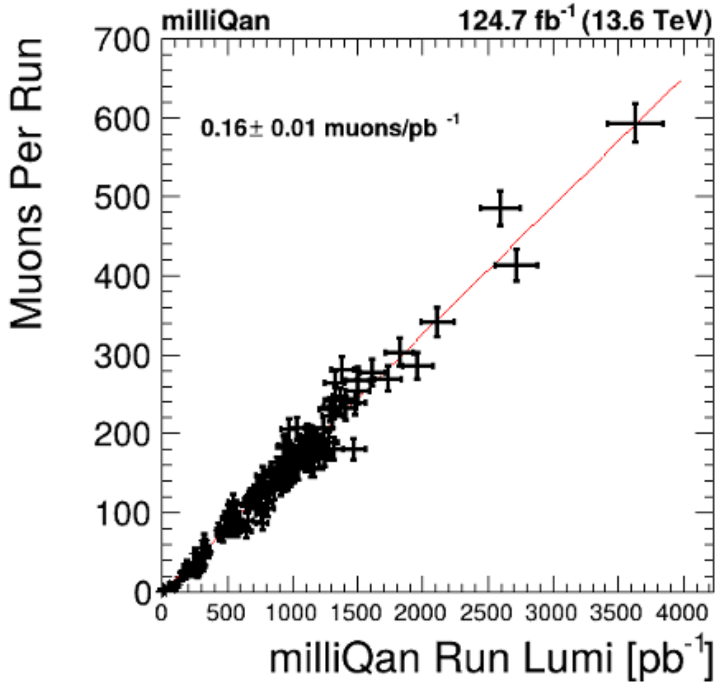
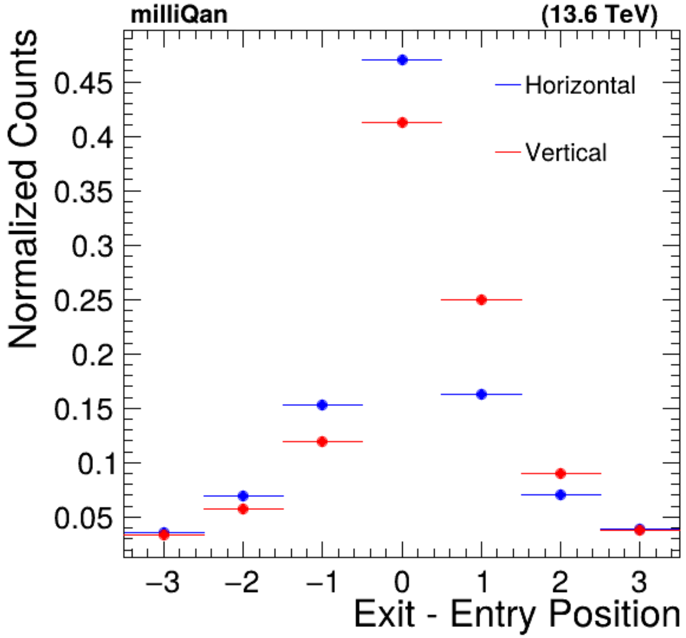
Validating simulation and alignment with muons

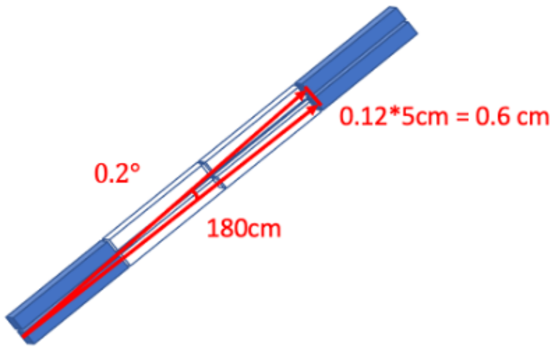
Muon rates



Alignment



difference → ~0.2° misalignment



Corrected 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:

  observed $0.16 \pm 0.01\ \mathrm{pb}^{-1}$ for $0.21 \pm 0.05\ \mathrm{pb}^{-1}$ expected

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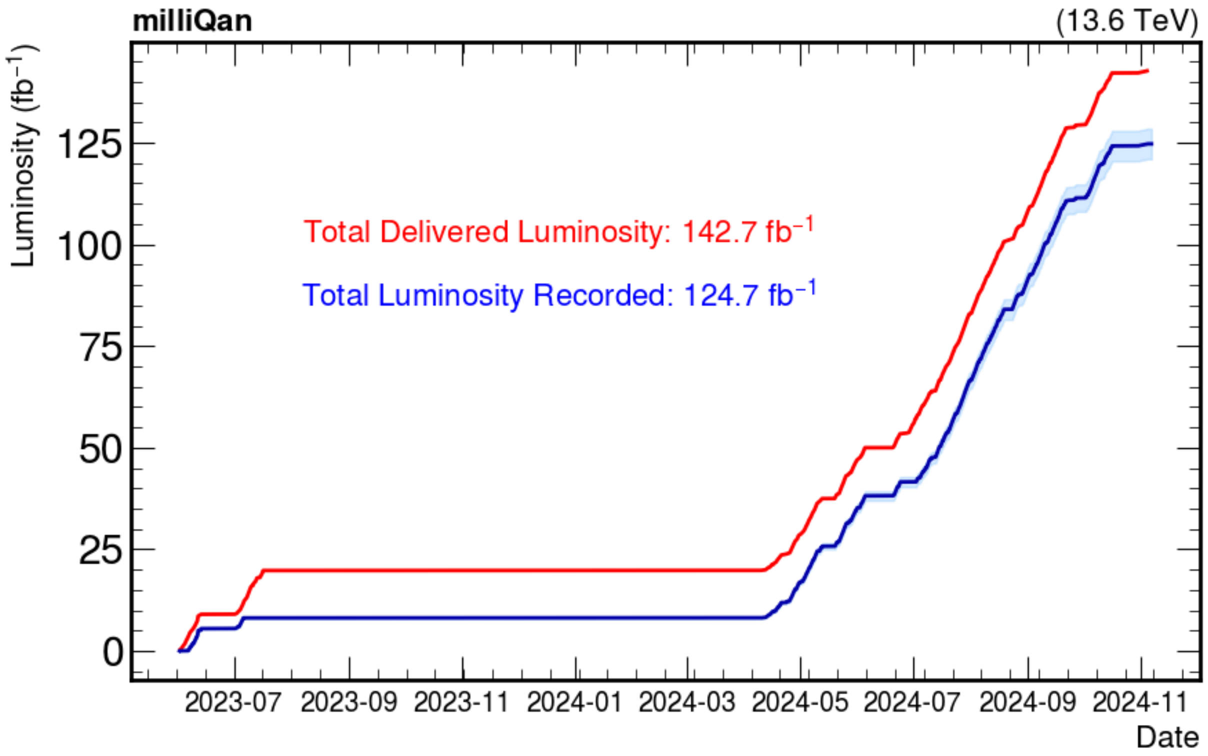
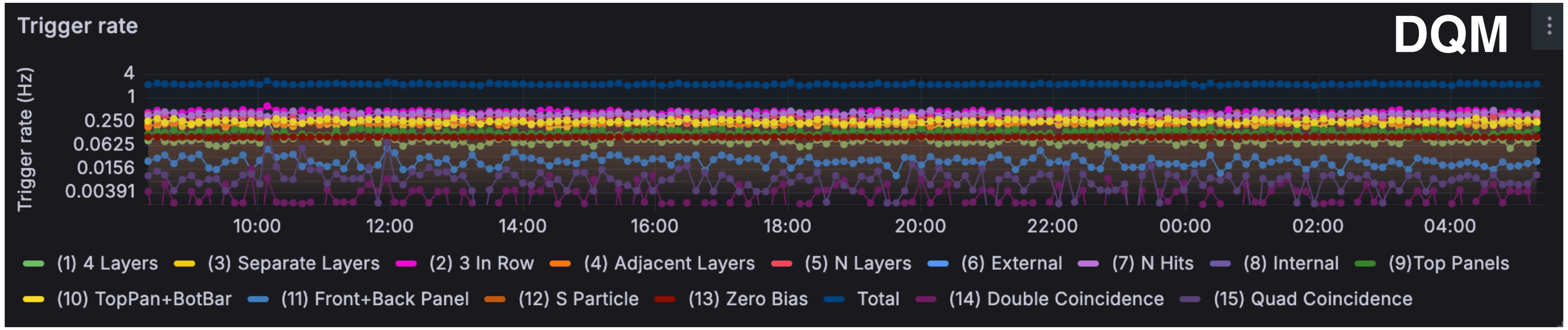
Run 3 search for mCPs, started in 2023

- 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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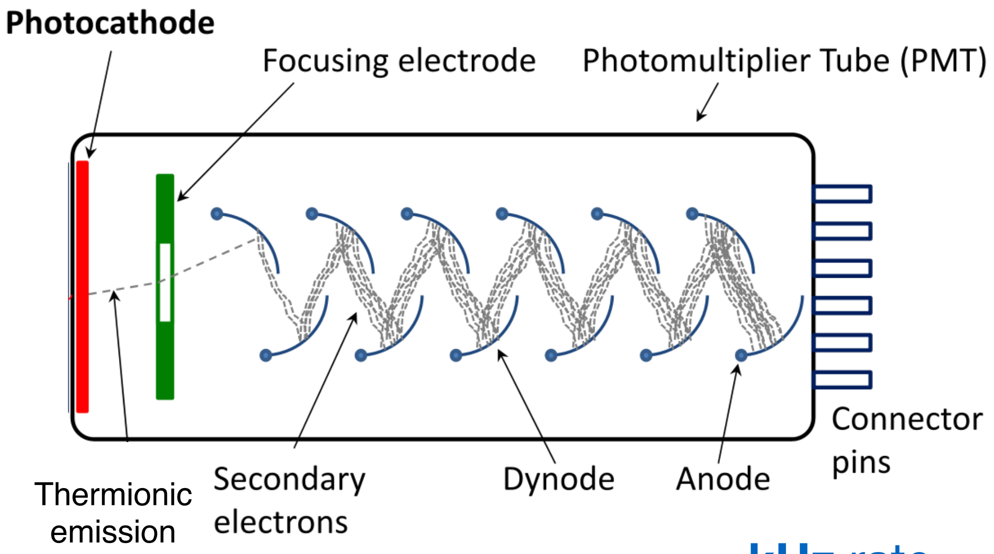
Main mCP backgrounds + mitigation

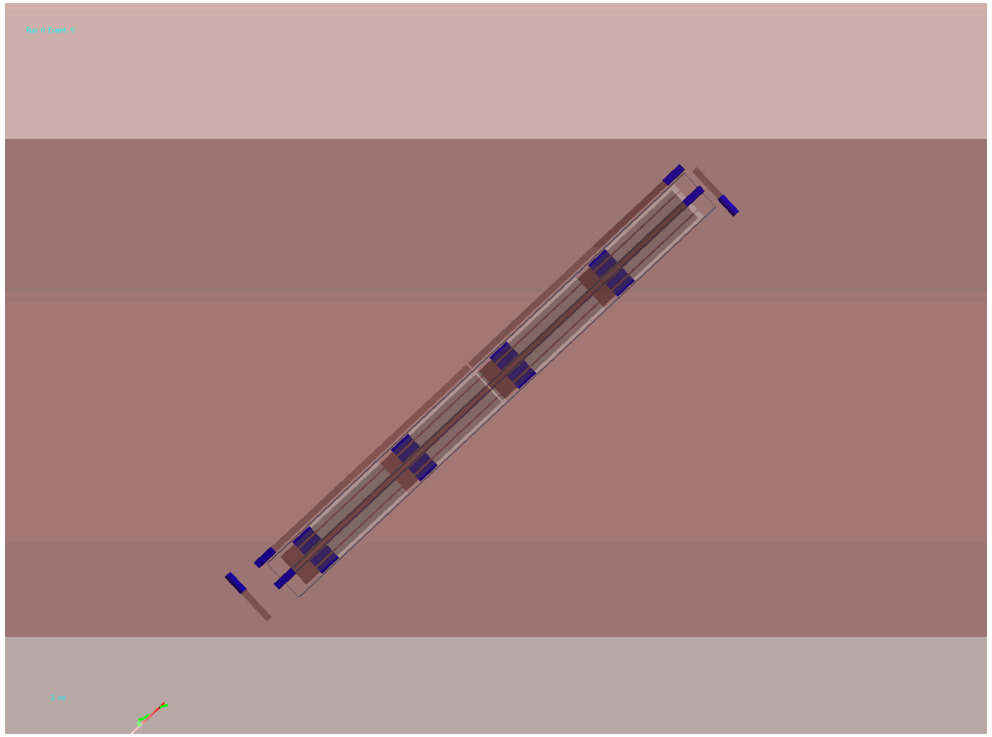
Background: PMT dark rate (random in time)



~ **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**

Full range of selections reduce backgrounds by ~6 orders of magnitude

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Main mCP backgrounds + mitigation

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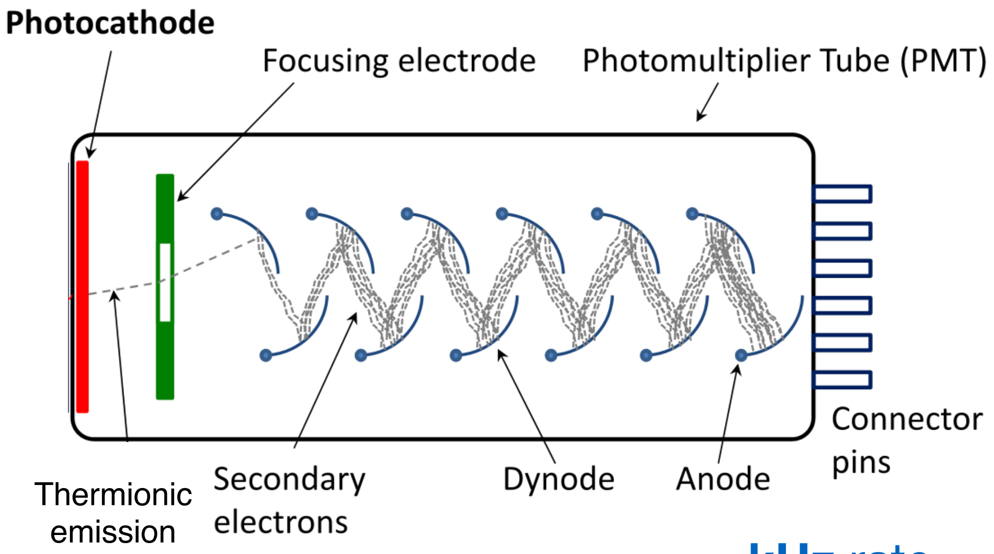

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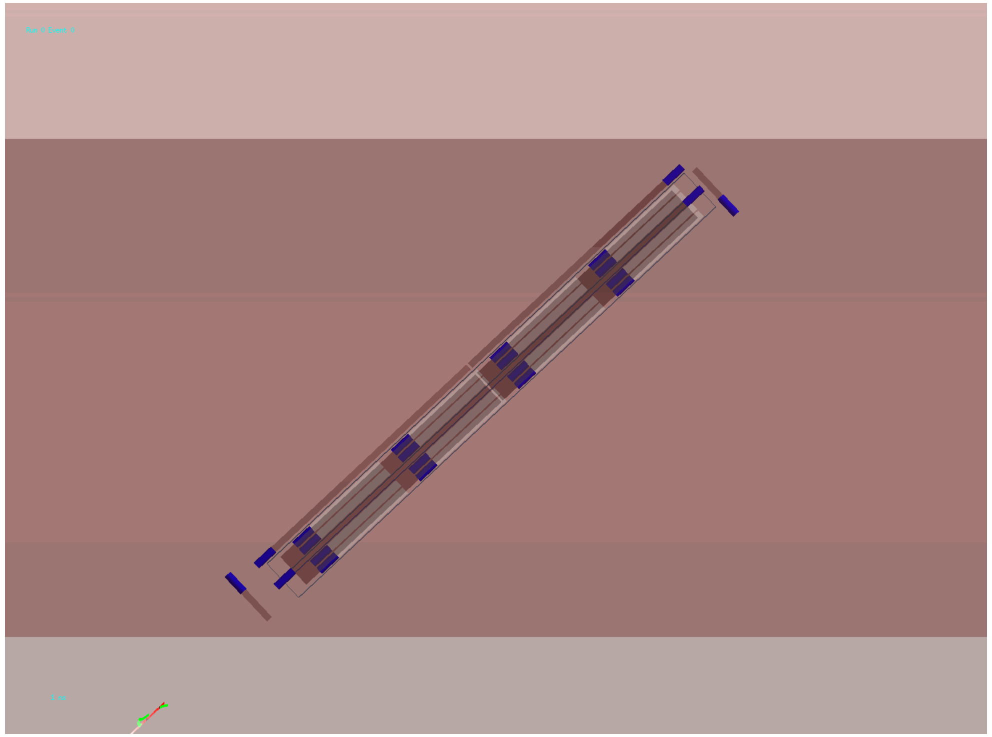

Veto events with **single** deposit per layer forming **pointing path** to I.P. **if** also have **deposits in side panels**

Full range of selections reduce backgrounds by ~6 orders of magnitude

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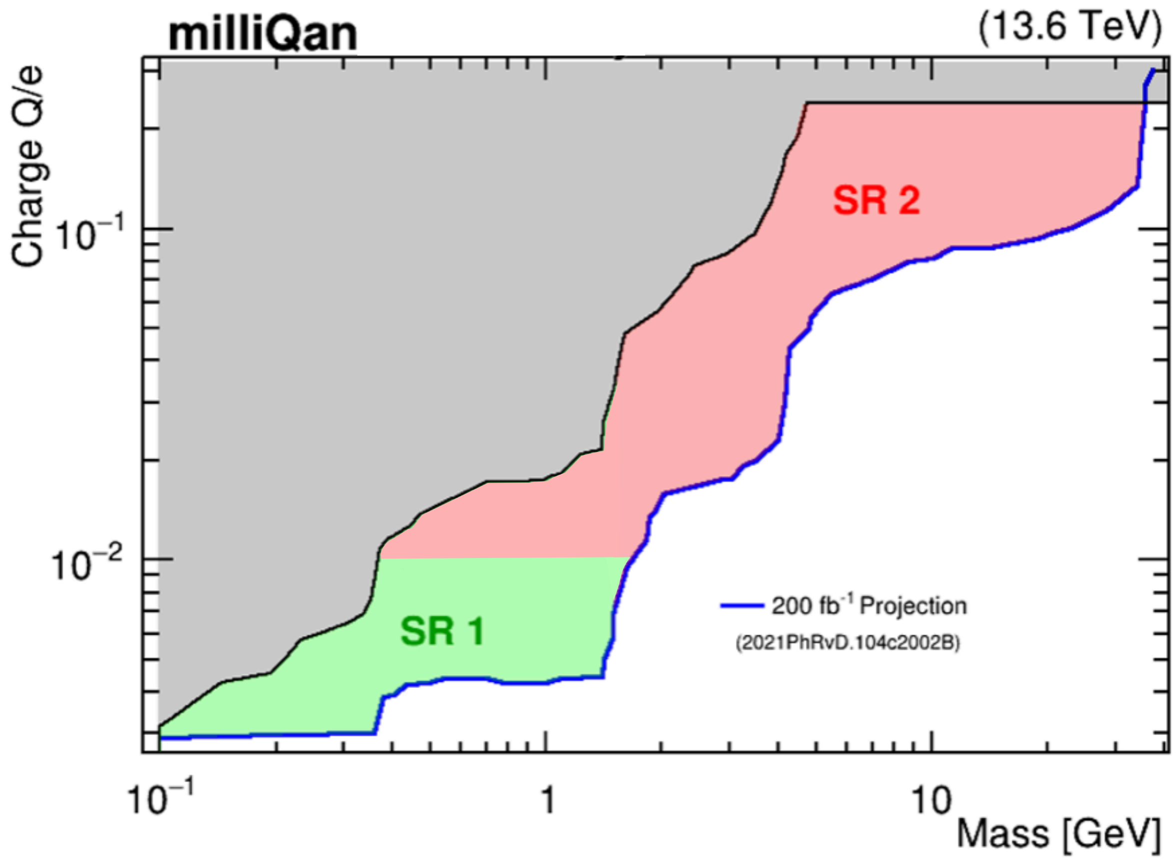
Search in two orthogonal signal regions

SR1: lower charges

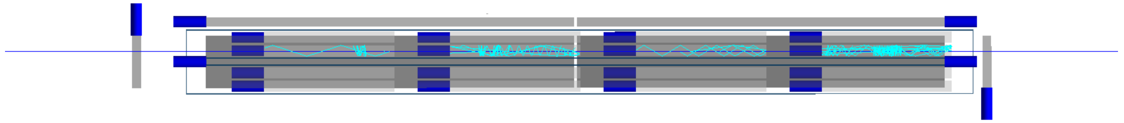
- **Veto** events with hits in **front/back panels** and **saturating pulses** deposited in any bar.

SR2: higher charges

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

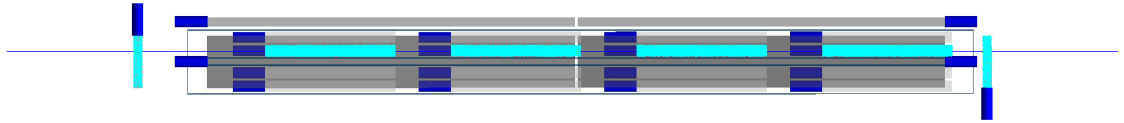


Q/e = 0.002



SR1

Q/e = 0.01



SR2

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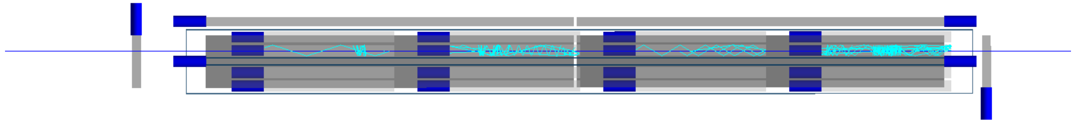
Background prediction/validation: SR1

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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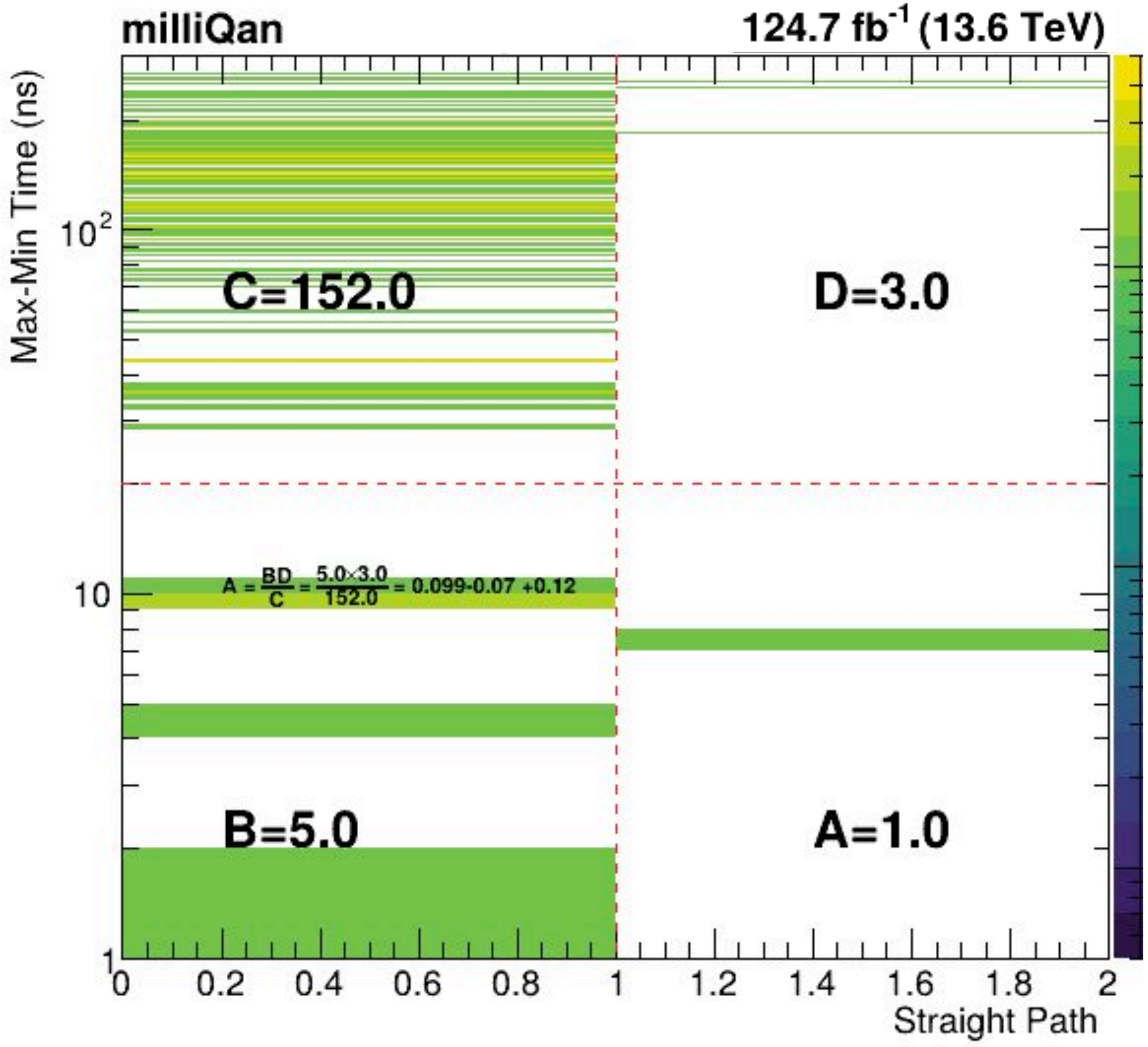
SR1 unblinding

- Prediction: $0.10^{+0.12}_{-0.07}$
- Observation: 1

Result:

Agreement within $\sim 1.6\sigma$

Mildly interesting?



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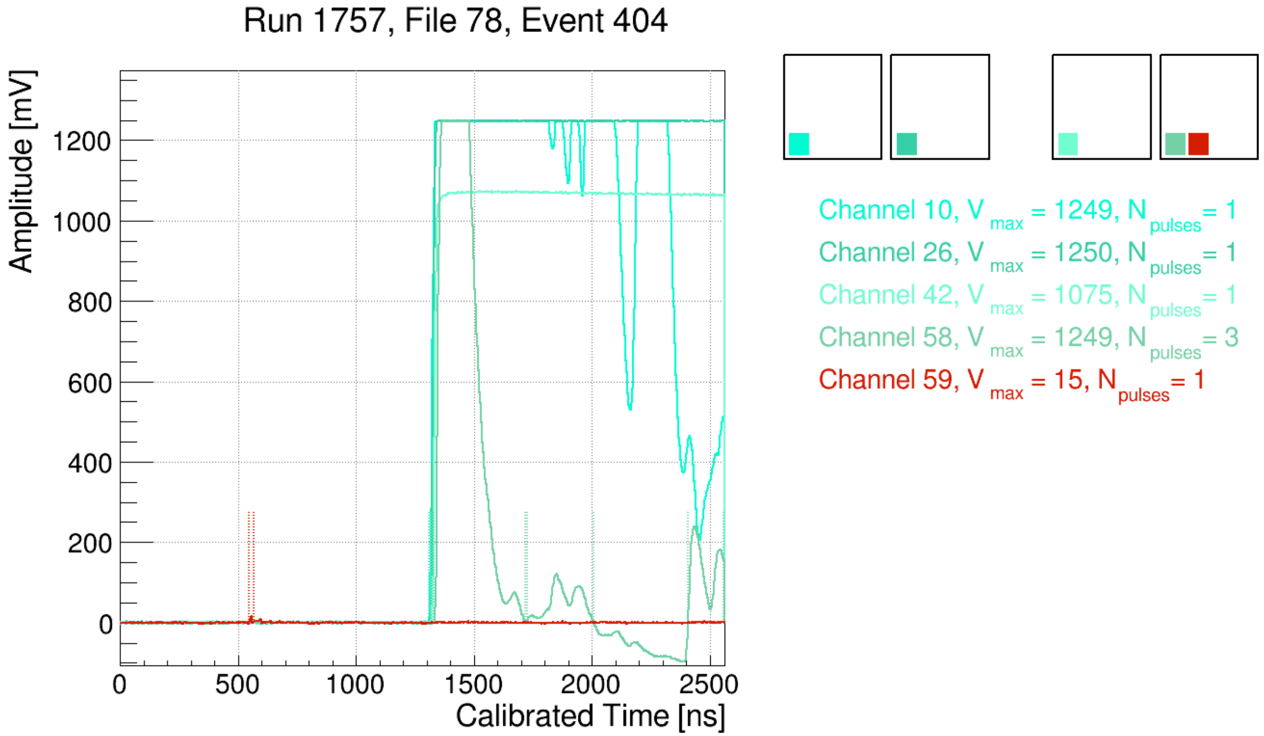
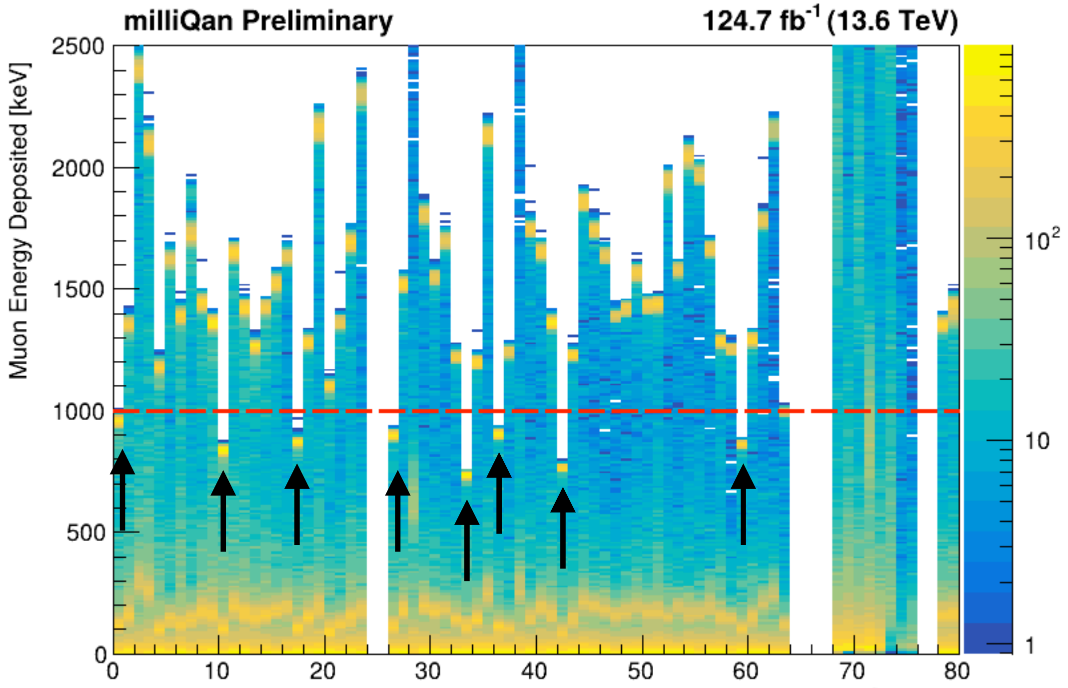
Muon veto fix

Multiple channels saturate full waveform
→ event should have failed muon veto



Multiple channels saturate at lower energy (inc 3/4 for excess event) - **muon veto threshold needs to be lowered for these channels**

NB: front/back panels not quite hermetic - will be fixed for 2025/2026 running



channels with early saturation

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

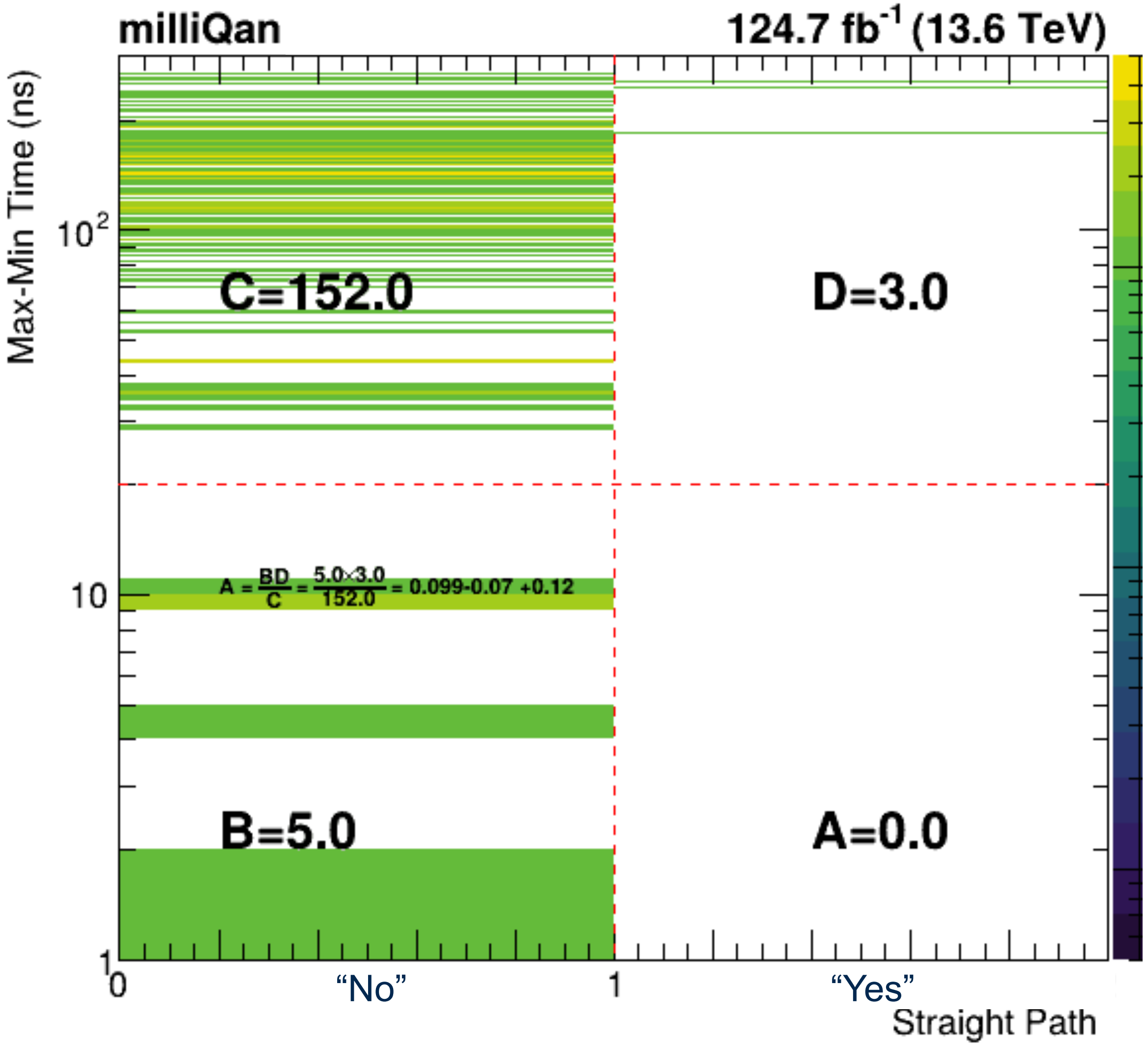
UCDAVIS

SR1 (re)unblinding

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

Result:

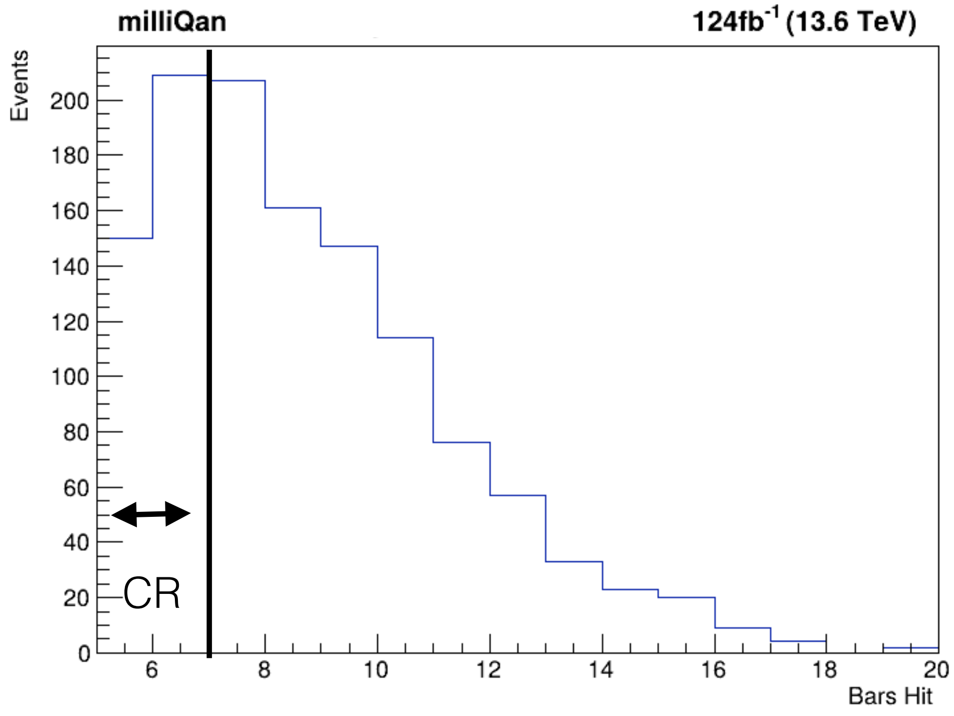
No mCP signal :(



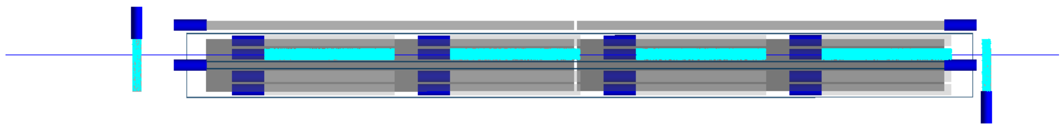
UCDAVIS

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

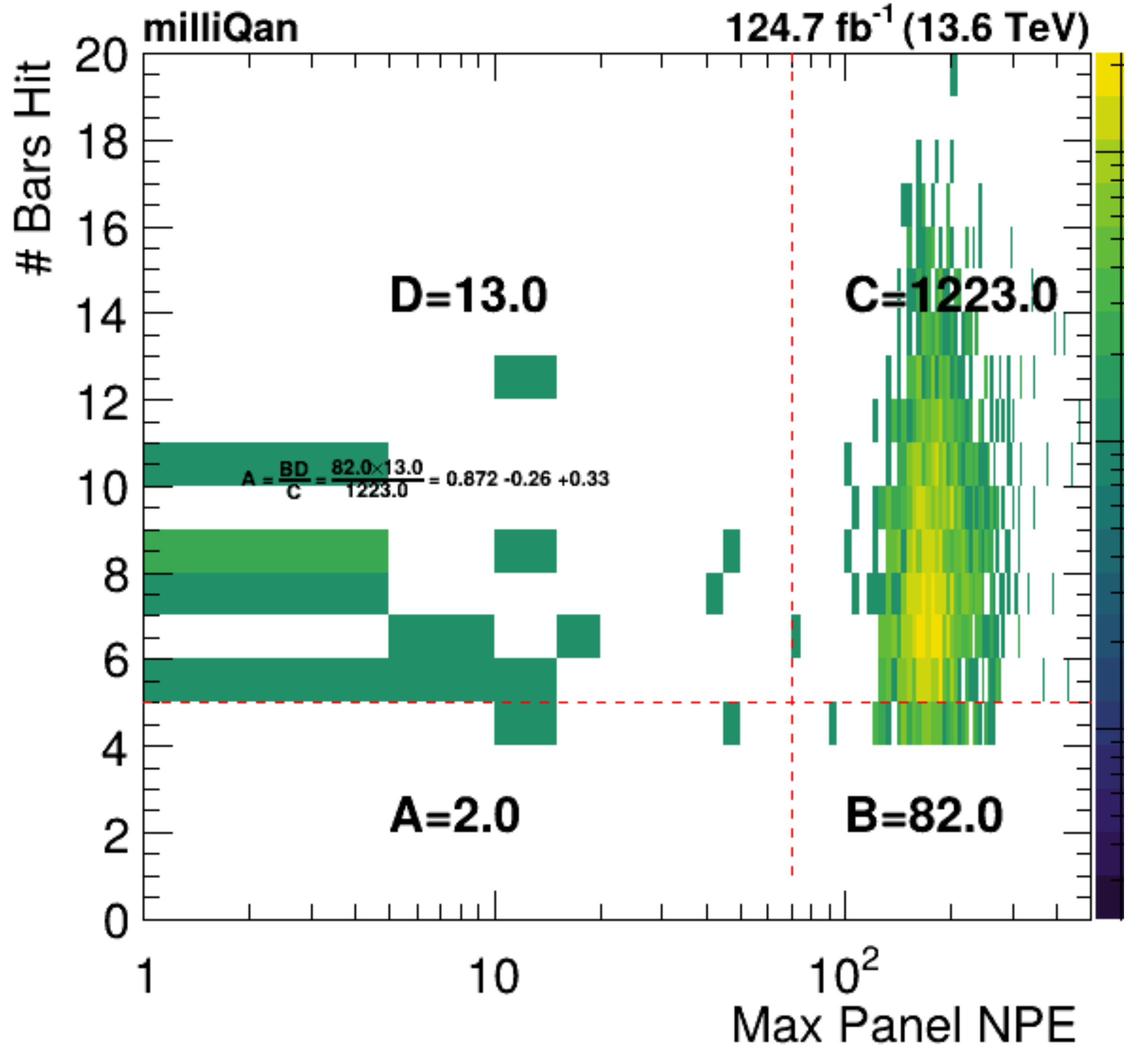
Observation: 5

UCDAVIS

SR2 search results

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

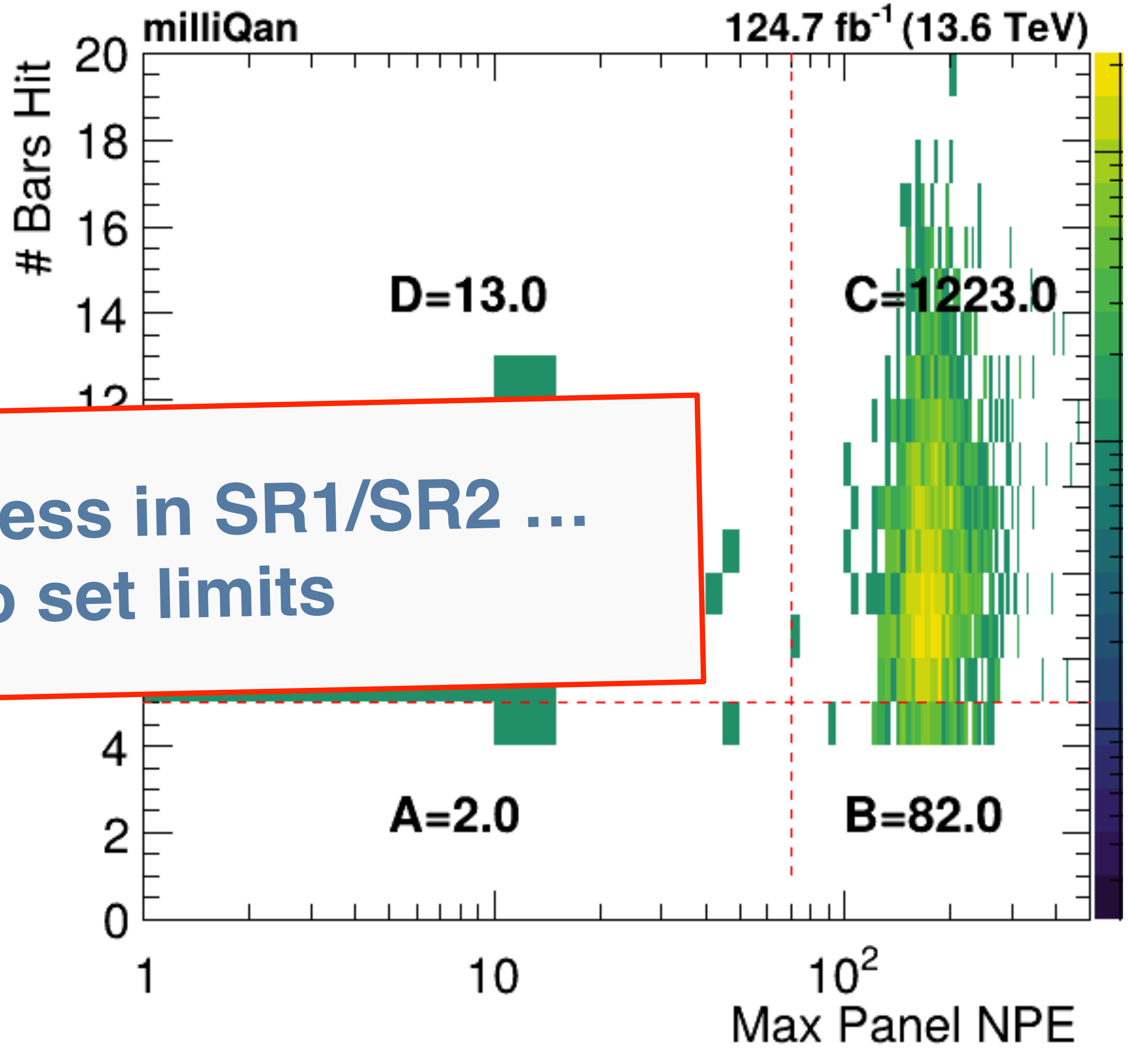
Result:
Agreement within ~1.2σ



UC DAVIS

SR2 search results

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



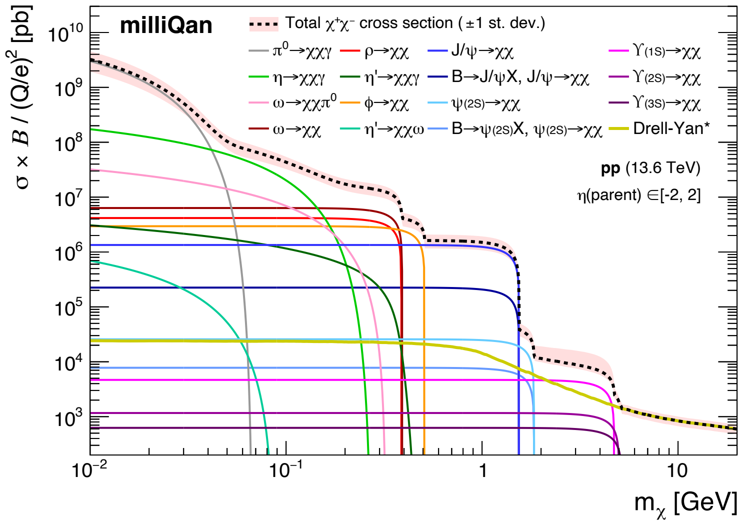
No significant excess in SR1/SR2 …
proceed to set limits

Result:
Agreement within ~1.2σ

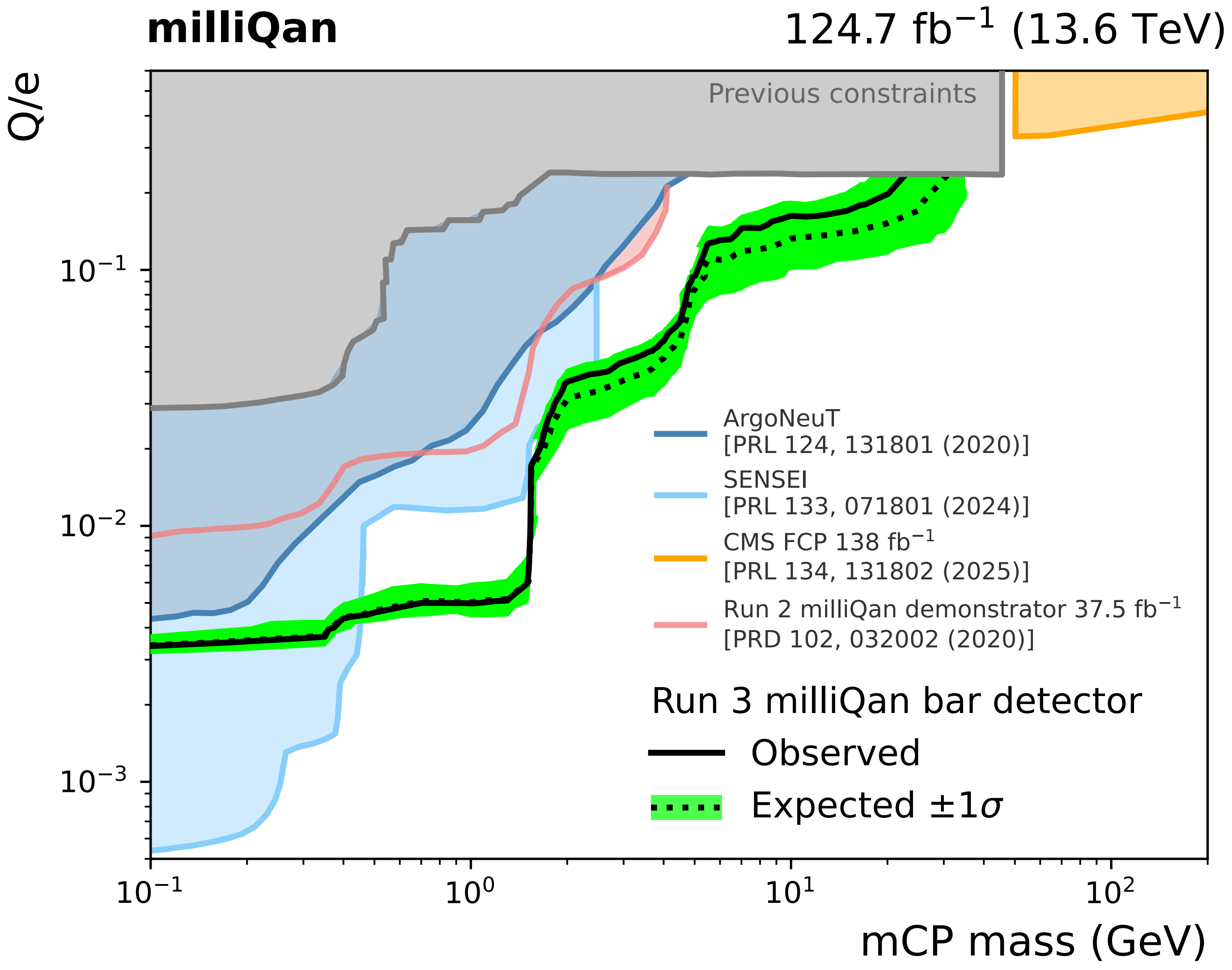
UCDAVIS

Search results!

- **World leading** limits on mCPs with masses 0.5 - 25 GeV!
- Only 40% of full Run 3 dataset analyzed → next years + slab to extend sensitivity significantly!



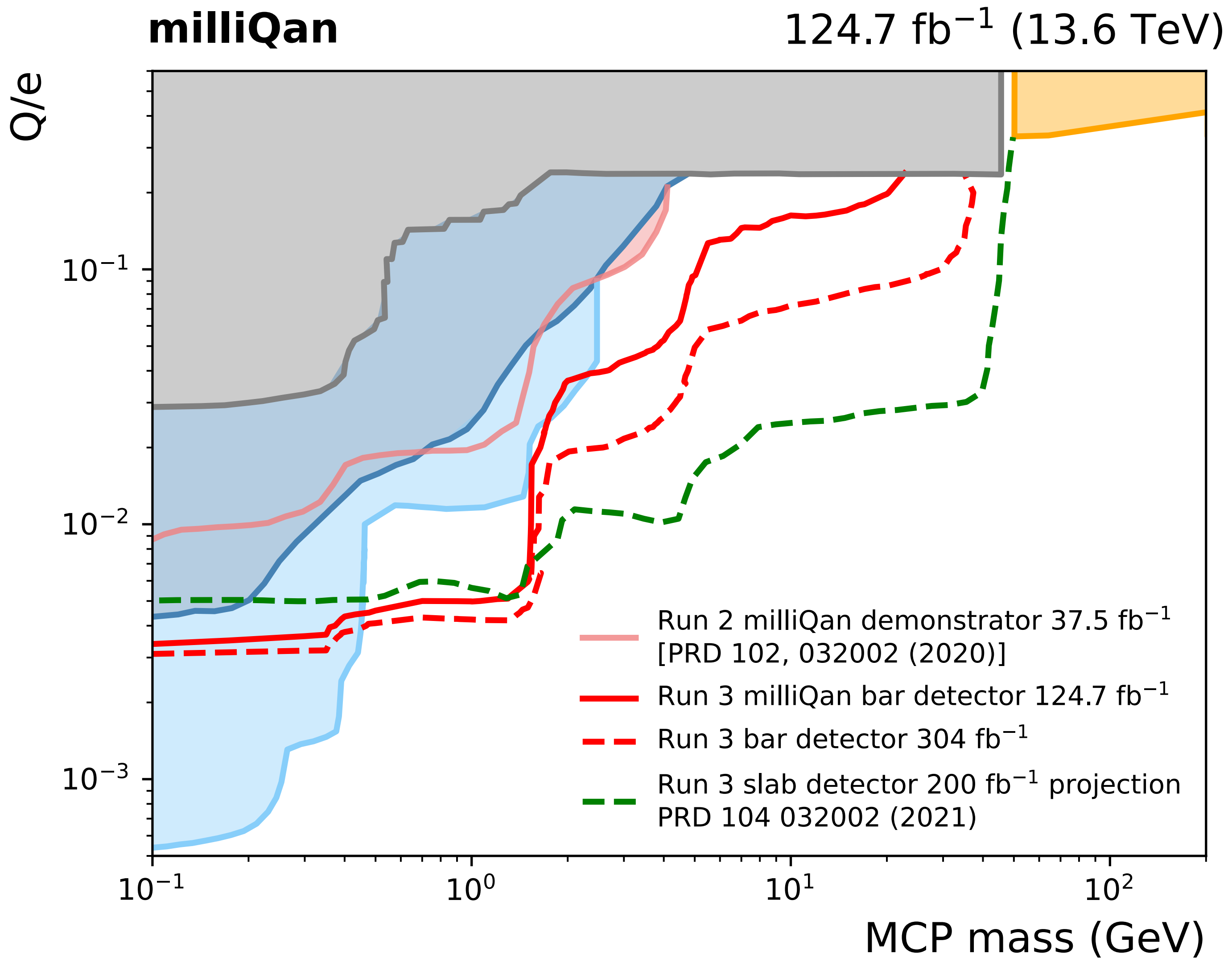
Signal simulation considers wide range of DY/meson production



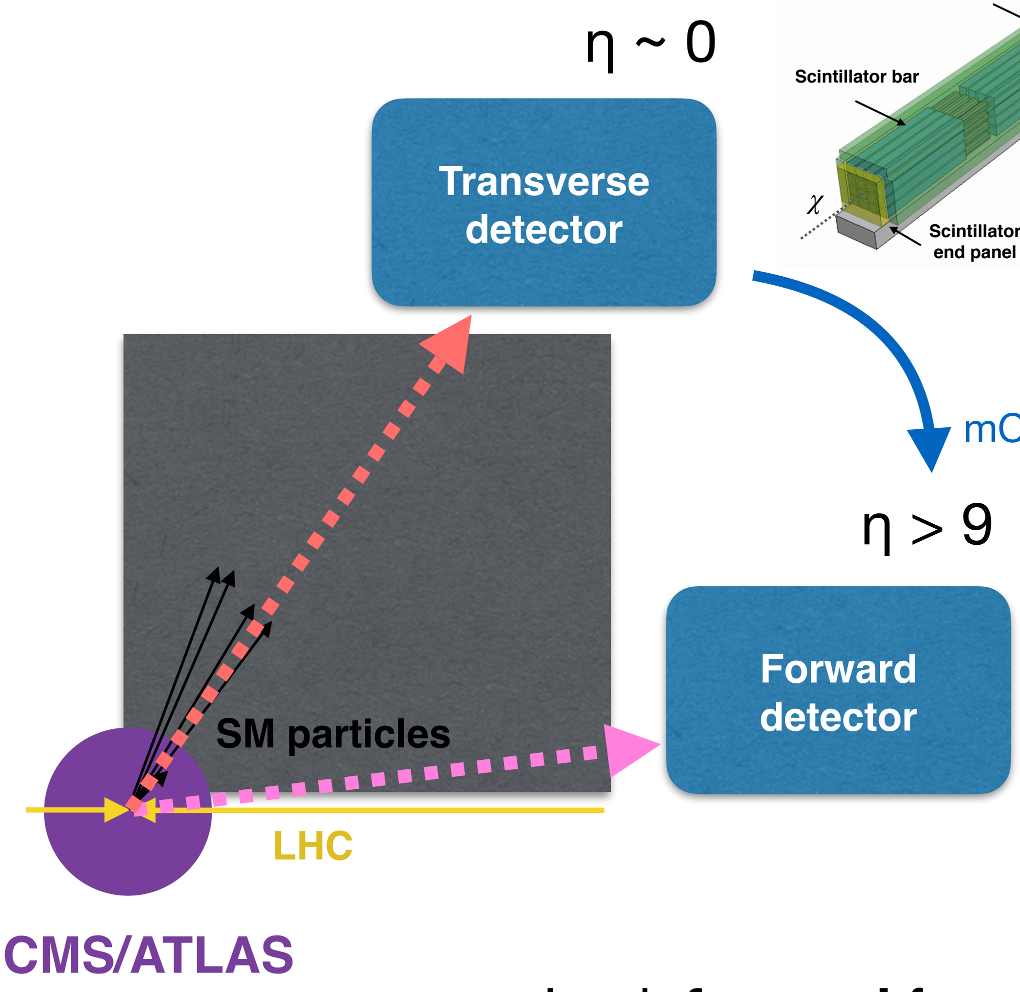
Paper available at https://arxiv.org/abs/2506.02251 !

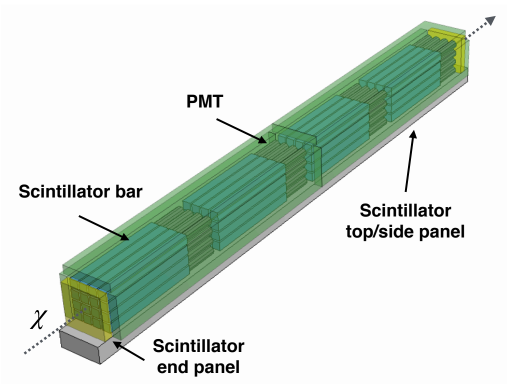
Expectation for full Run 3

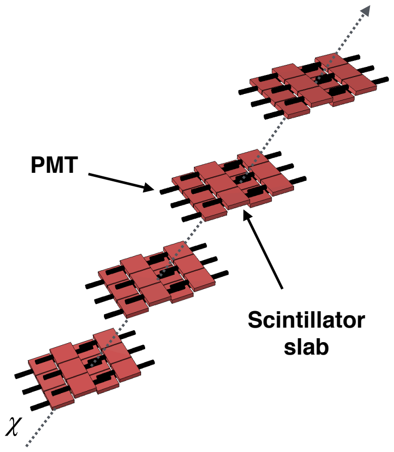
- Adding 2025+2026 data gives significant **guaranteed** extension in reach with bar detector
  - Addition of hermetic front panel will reduce background << 1 for SR2
- Search already designed, will allow rapid top up
- Slab detector is online for 2025 running will extend even further!



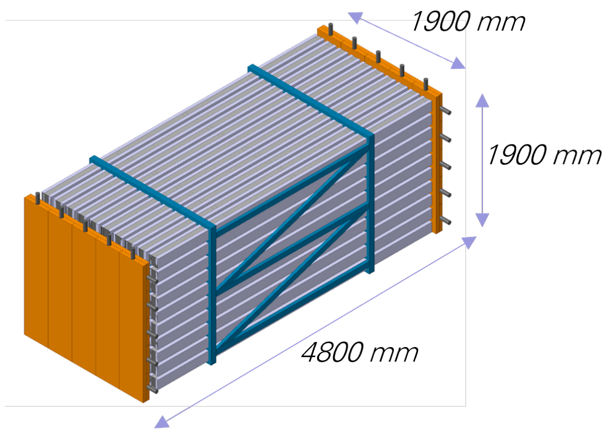
What's next at the LHC?







mCP flux over 1000 **times larger**!

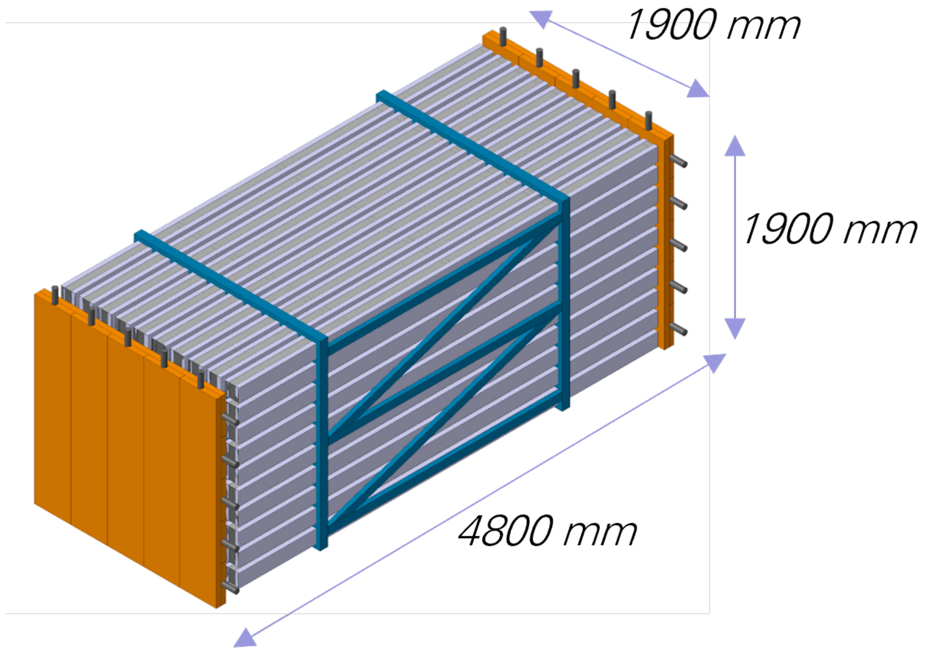


Look **forward** for greatly increased production

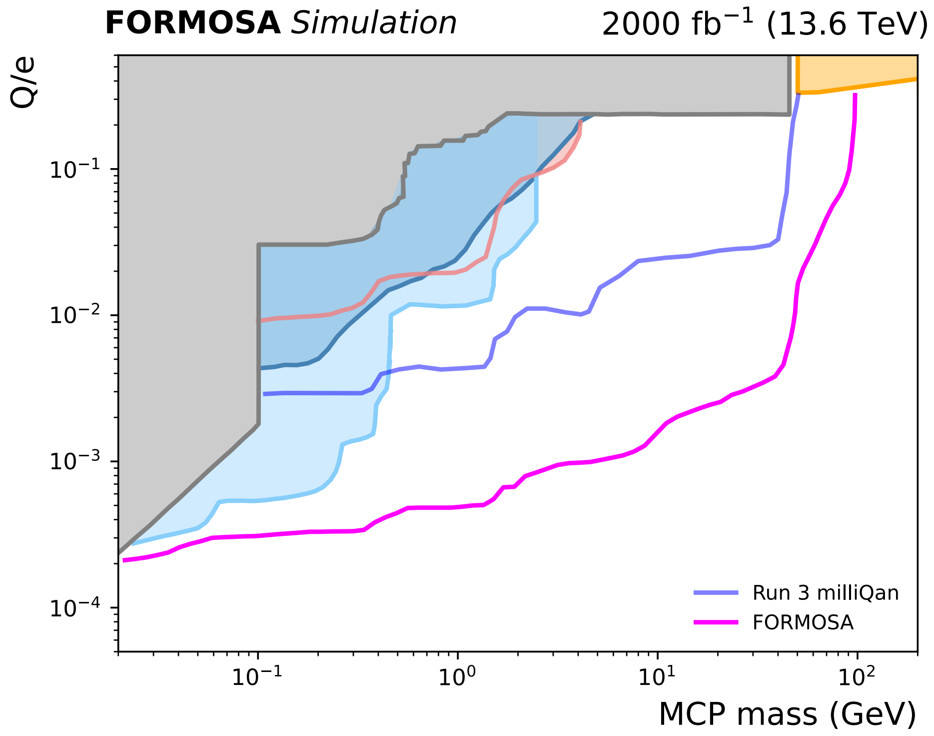
FORMOSA

FORMOSA: 20x20x4 array of plastic scintillator bars (EJ-200) coupled to Hamamatsu 7725 PMTs

Ideal location: proposed “Forward Physics Facility” ~600m from ATLAS IP (see backup)



FORMOSA design in [FPF paper]



- World leading sensitivity across wide range of masses!
- New **challenge**: forward region location gives rise to a new background: “afterpulsing” from beam muons (muon flux ~1/cm^2/s) → installed demonstrator to prove feasibility

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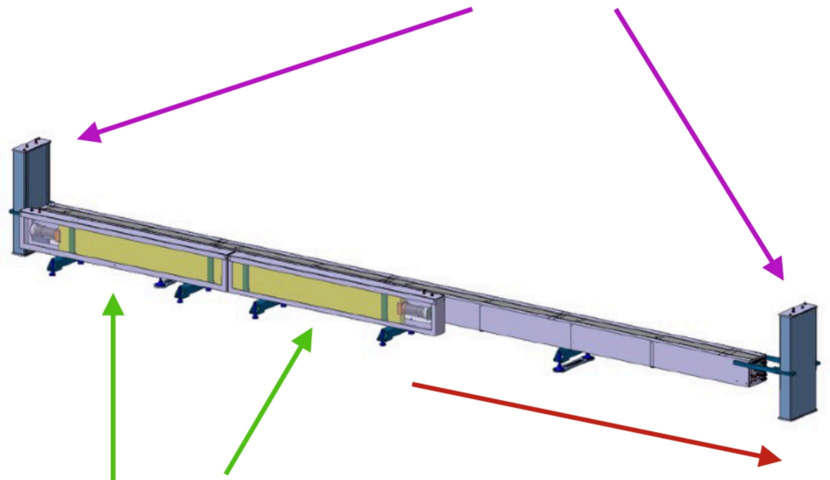
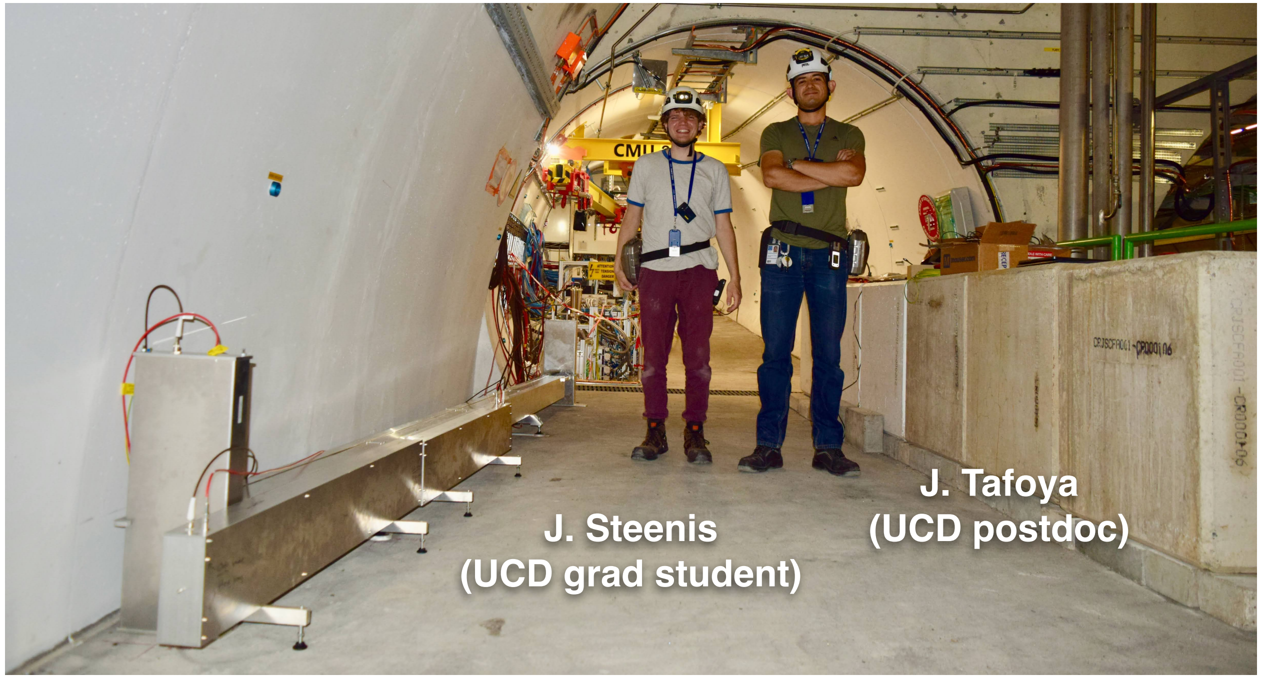
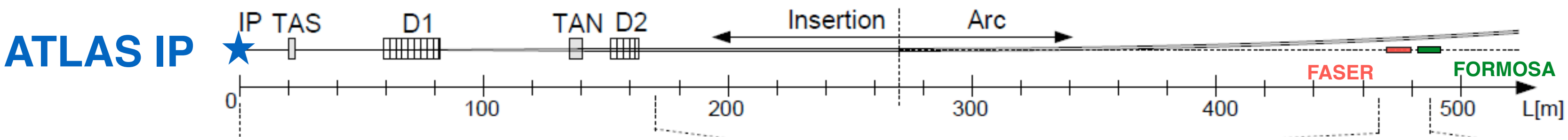
The FORMOSA demonstrator







A small-scale version of the full FORMOSA detector installed behind FASER Feb 2024 (2x2x4 bars + veto panels)

Goal: validate **DAQ strategy**, **measure backgrounds** and prove search for mCPs is **feasible** in the forward region

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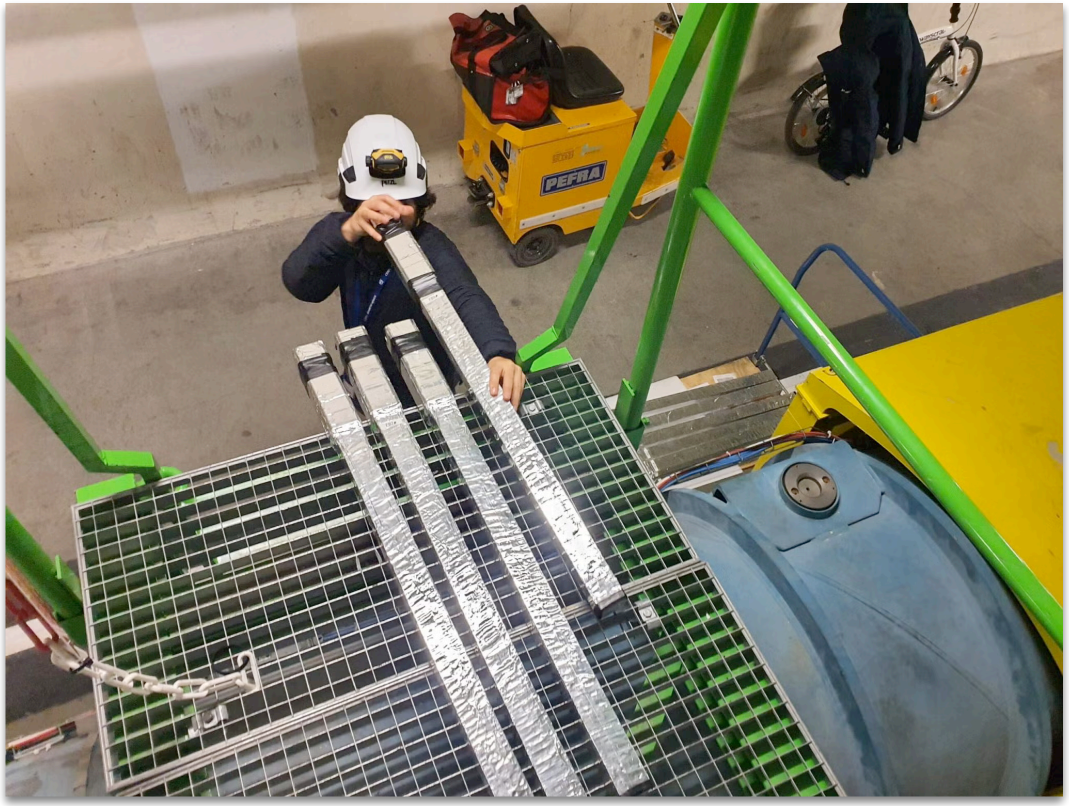
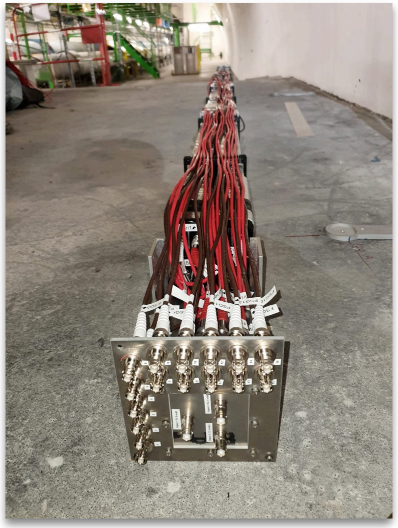
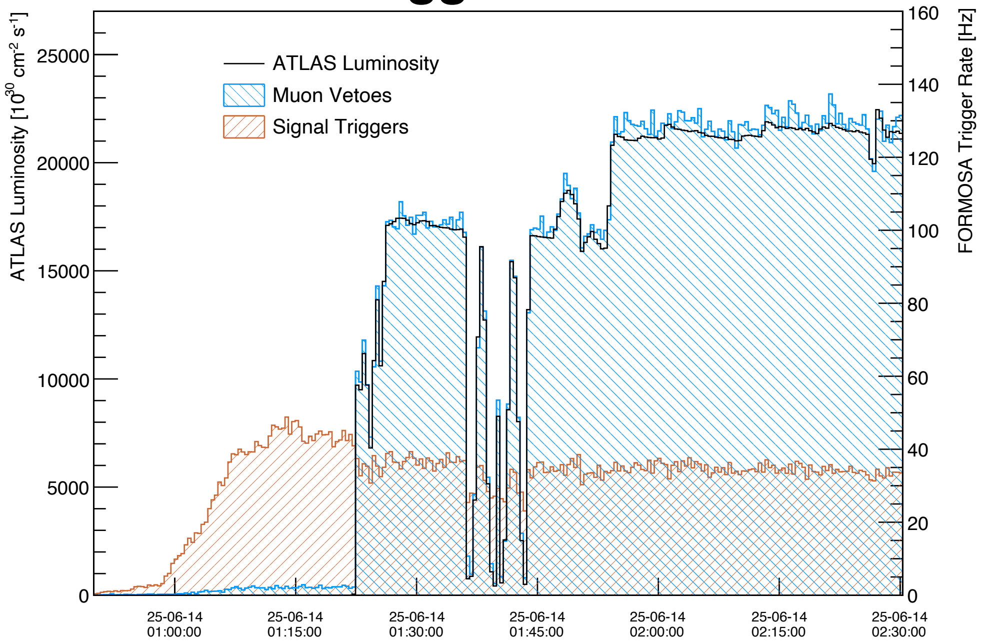
Installation (Feb 2024)





Detector commissioning

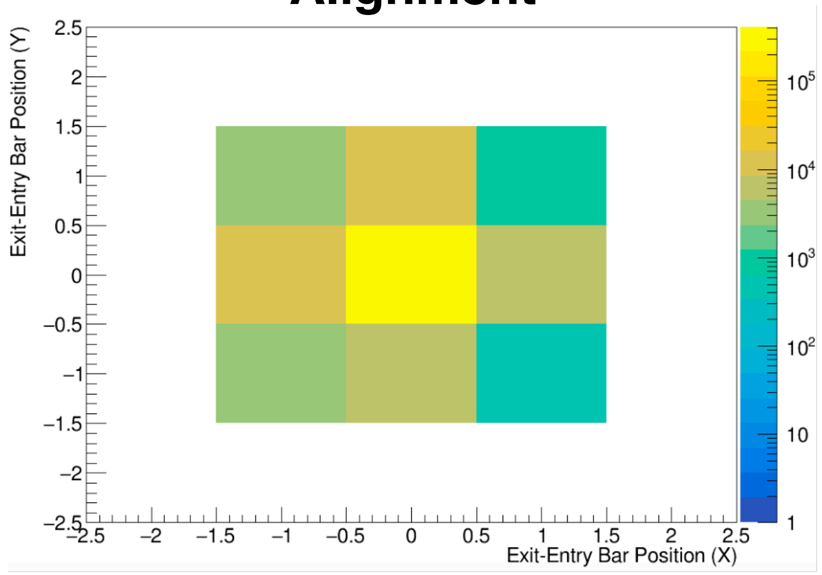
Trigger rates



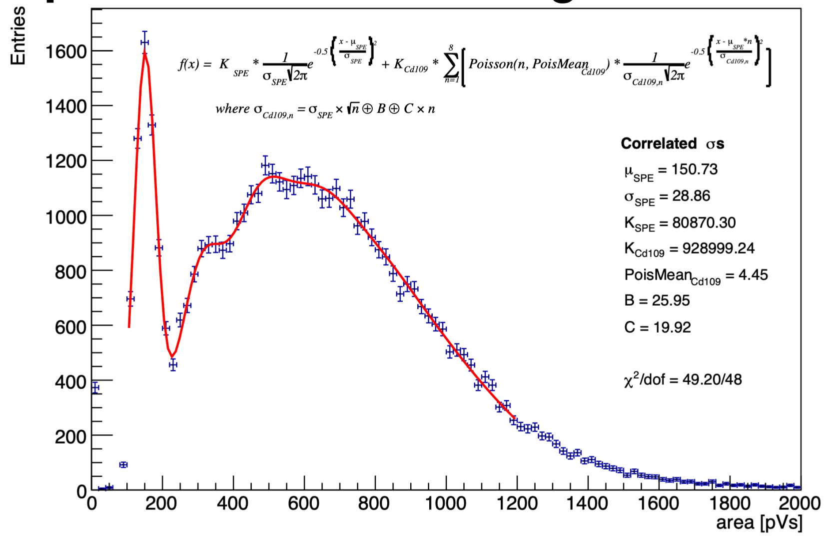
Signal triggers stably collecting data

Muons very effectively vetoed!

Alignment



Response calibration using Cd_{109} source



- DAQ system **fully validated**: we can efficiently veto muons and beam related backgrounds!
- **Response, timing, alignment** fully calibrated/validated

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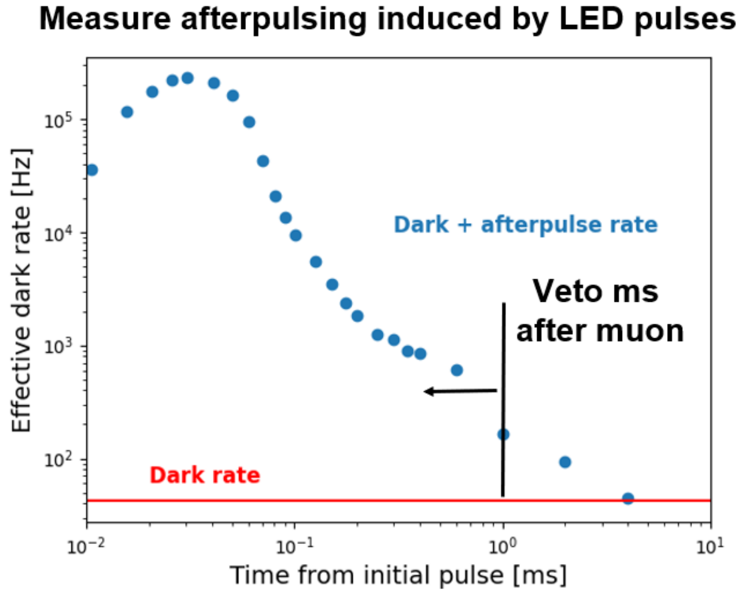
Muon veto and afterpulsing

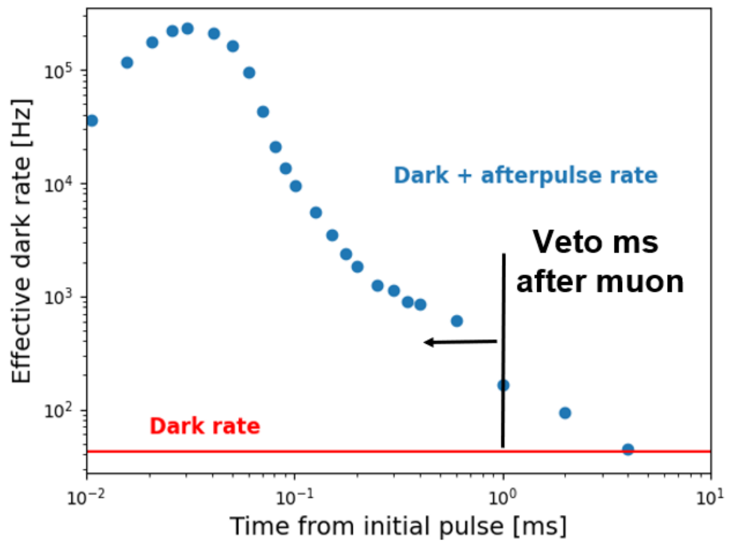


Study done for a single PMT suggests 1 ms of deadtime is enough

For ~100 Hz rate of muons, this corresponds to 10% deadtime

Muon veto and afterpulsing

Measure afterpulsing induced by LED pulses



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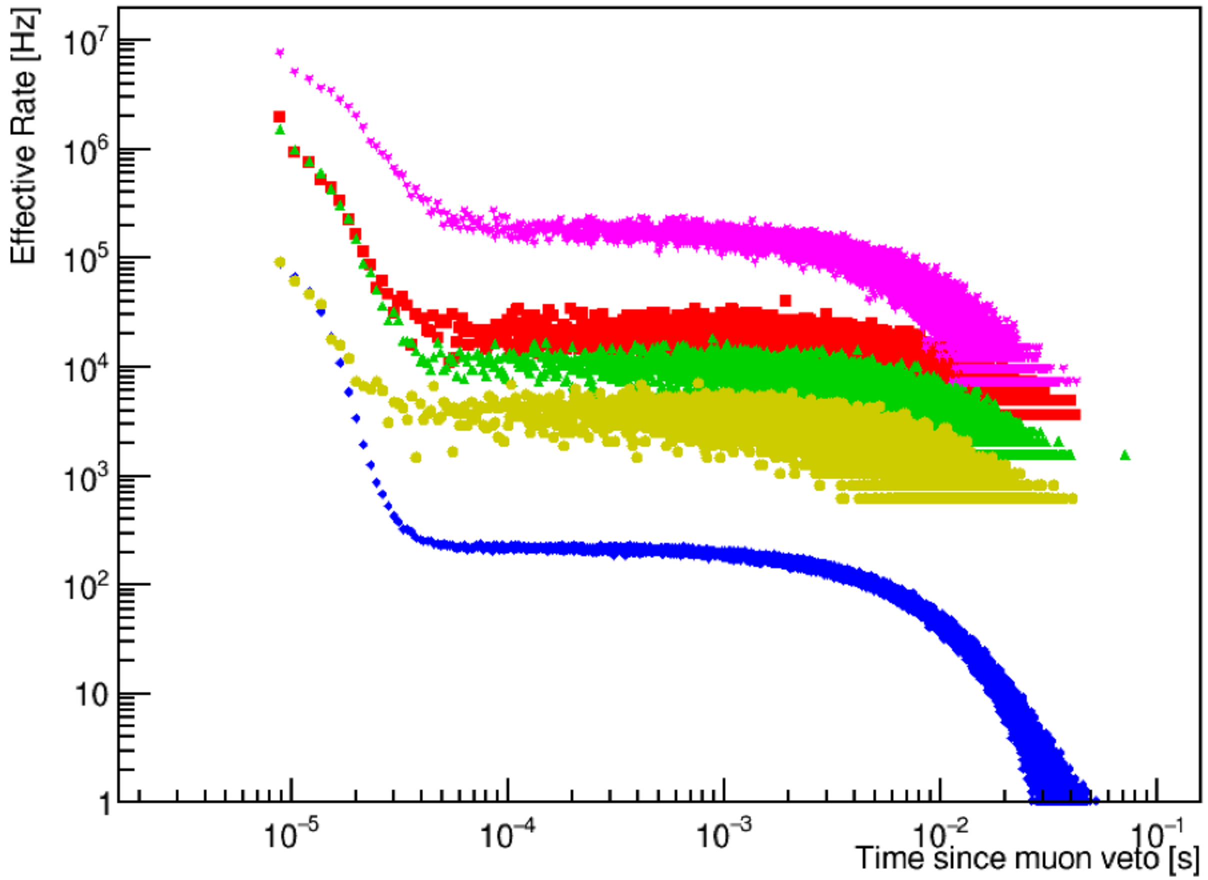
Comparing Post-Muon-Veto Rates for FORMOSA Triggers



Signal triggers

4Layers

nLayers≥3

nBars≥3

2Layers (both)

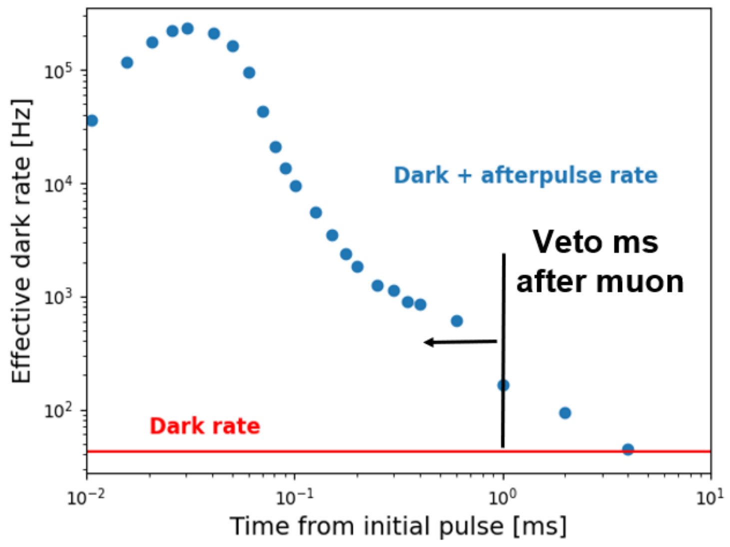
Special run with no muon deadtime

Overall scaling still in progress

UCDAVIS

Muon veto and afterpulsing

Measure afterpulsing induced by LED pulses



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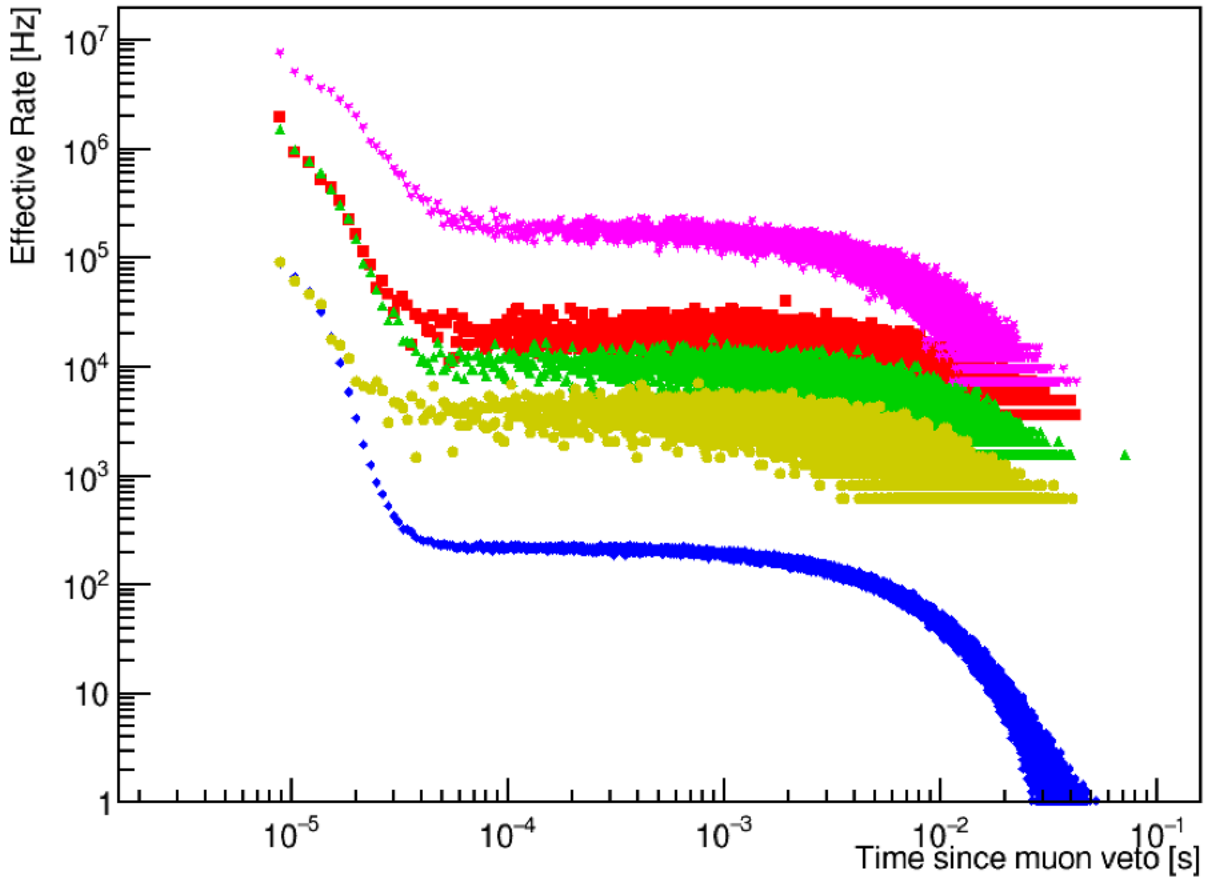
Comparing Post-Muon-Veto Rates for FORMOSA Triggers



Signal triggers

4Layers

nLayers≥3

nBars≥3

2Layers (both)

Special run with no muon deadtime

Overall scaling still in progress

Data suggest 100 μs deadtime is enough for signal triggers to recover back to nominal/healthy rates!
This corresponds to 1% deadtime

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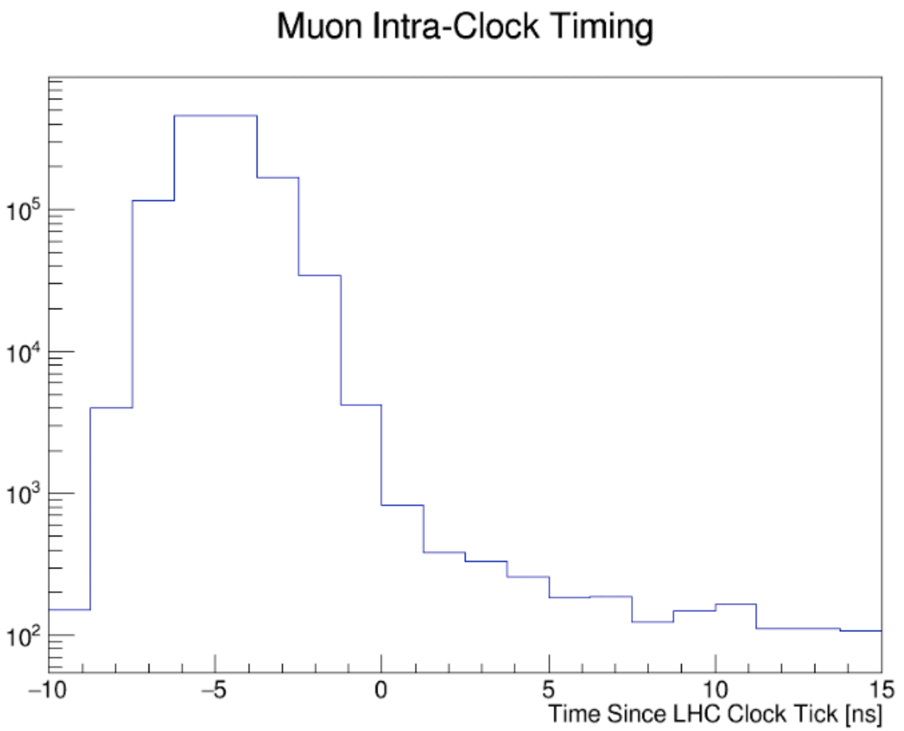
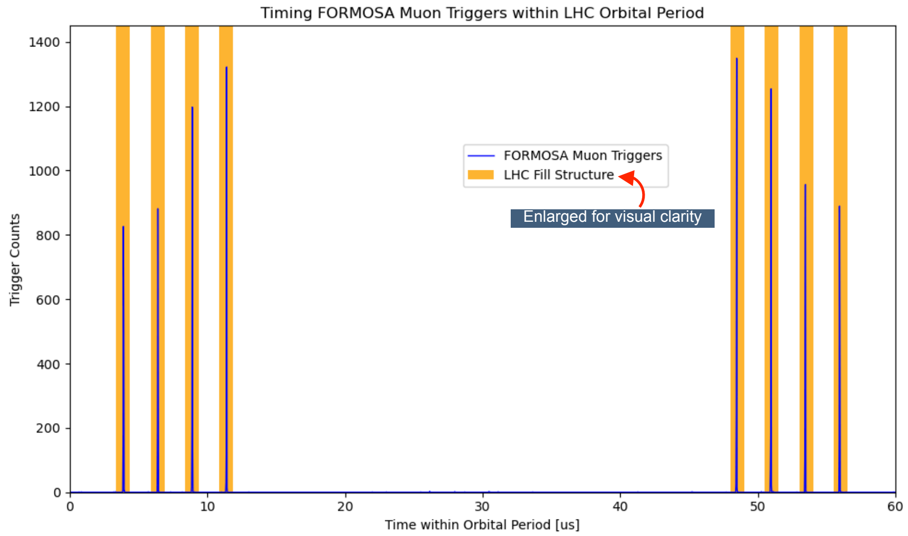
Timing studies



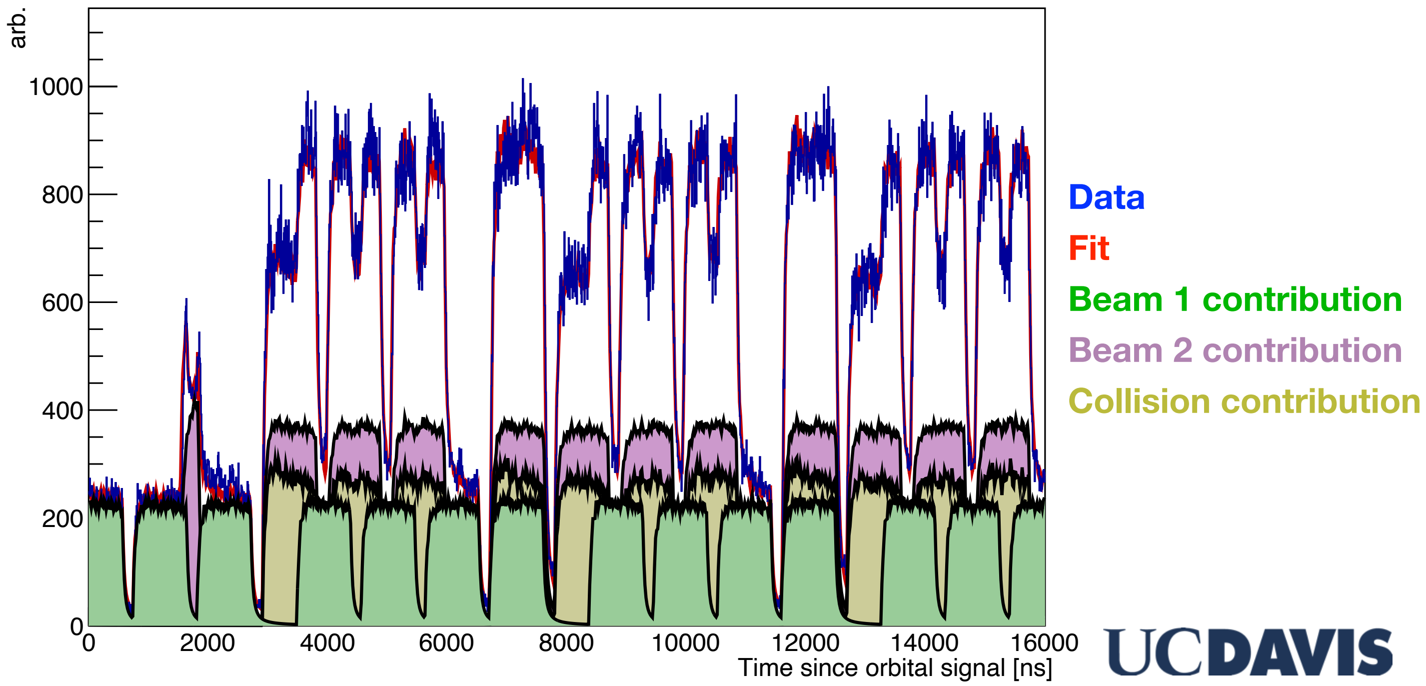
Muon arrival peak **Flat beam background**

*Looking **between LHC clock-ticks***

*Looking **within orbital** of a 12b fill with 8 colliding bunches*



*Looking **within orbital** of a standard fill*



Extremely valuable information for signal/background separation!

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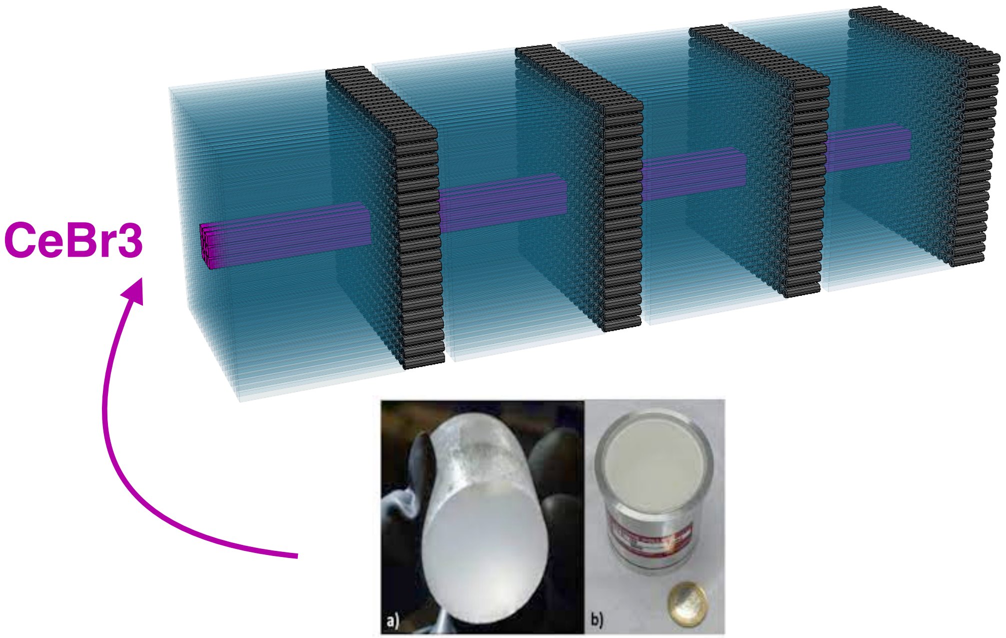
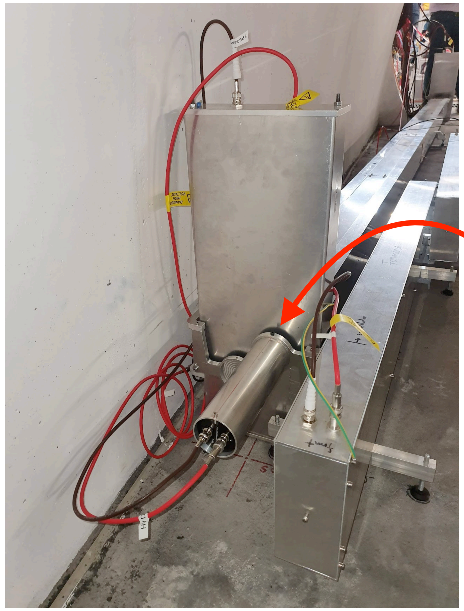
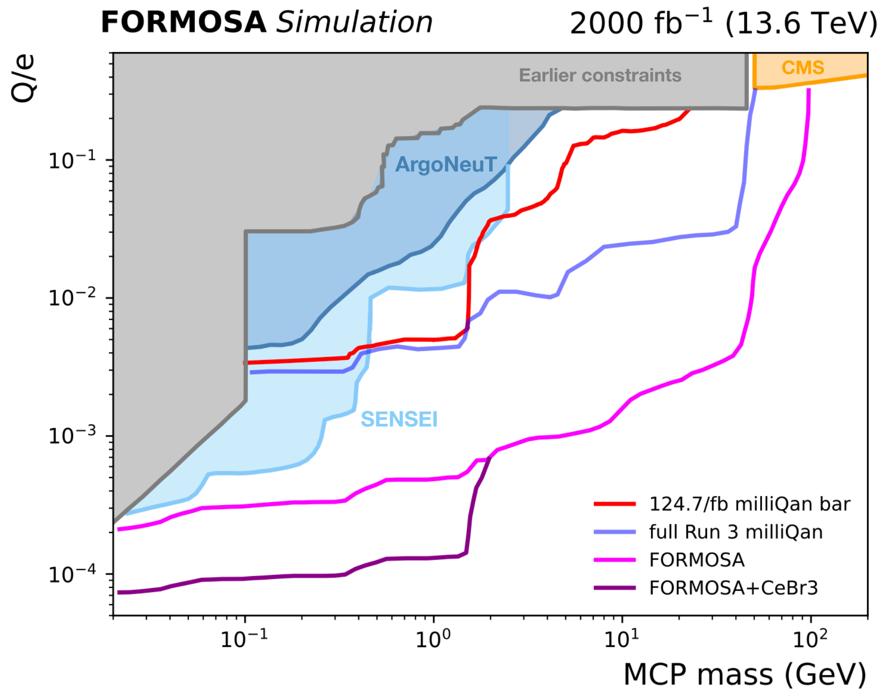
FORMOSA: CeBr3 module





Incorporated CeBr3 module into demonstrator in Sept 2024

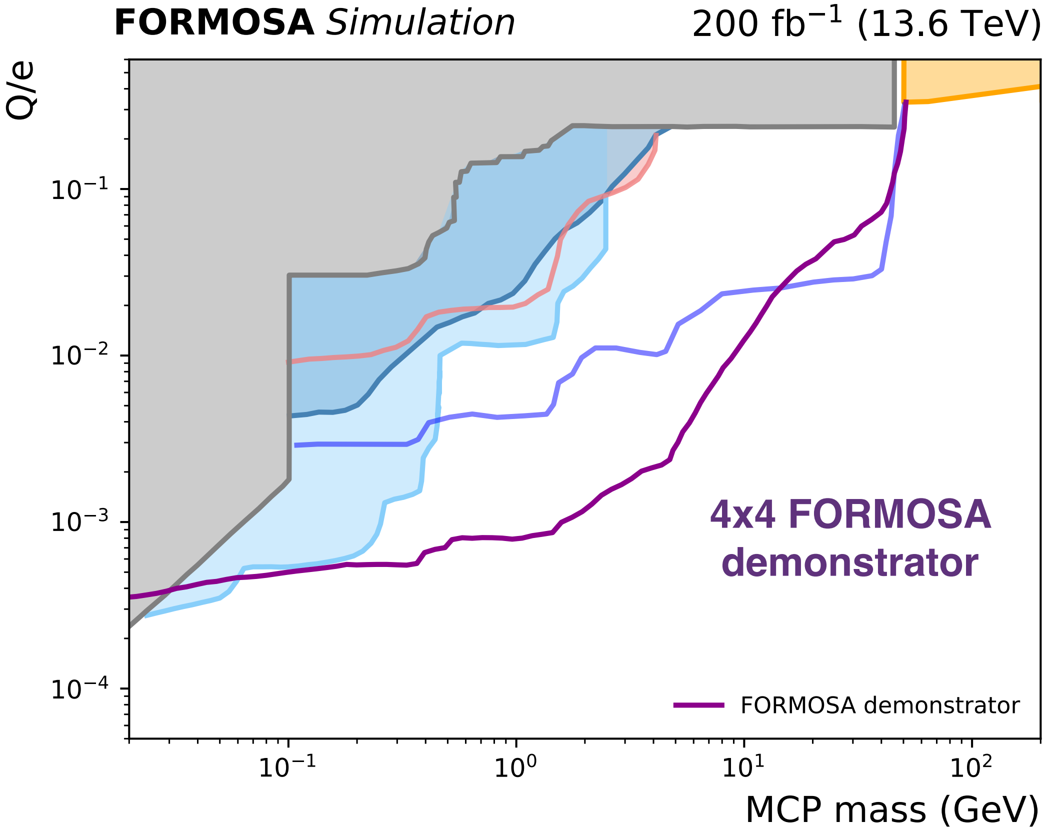


Investigate feasibility of FORMOSA subdetector made from CeBr3

- Factor ~35 larger light yield for same length compared to plastic, fast with low internal radioactivity

Considerable sensitivity gain possible! Studies ongoing using test module

The future for FORMOSA

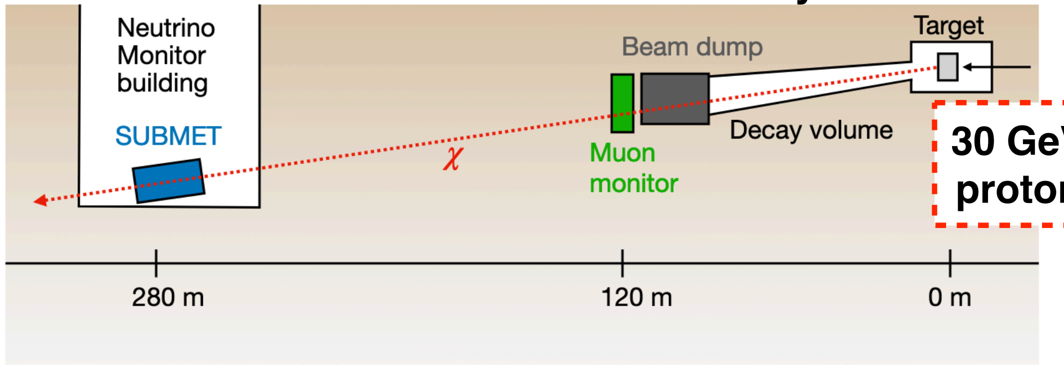


- Added LHC clock information to DAQ to **allow improved background characterization** and **veto**!
- Hermetic veto panels added over last couple months: **will attempt search with 2025 LHC data!**
  - Beam backgrounds additional challenge in FASER location
- Expand demonstrator size for early HL-LHC if funding allows

Looking beyond the LHC

Exploit high intensity facilities for ≲ GeV mcp sensitivity!

Sensitivity for m < ~1.5 GeV

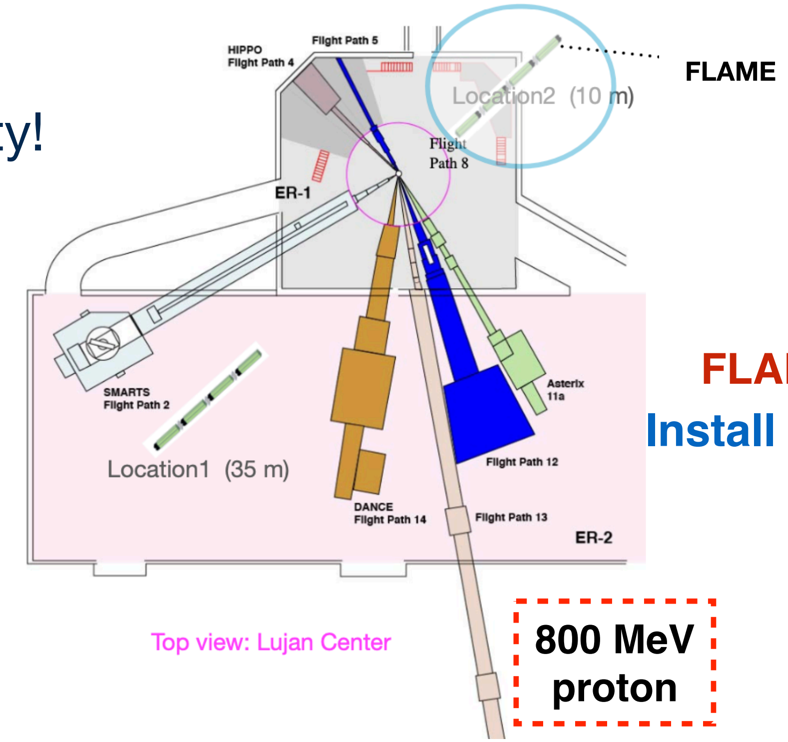


30 GeV proton

SUBMET at J-PARC

Finished first year of three year run!

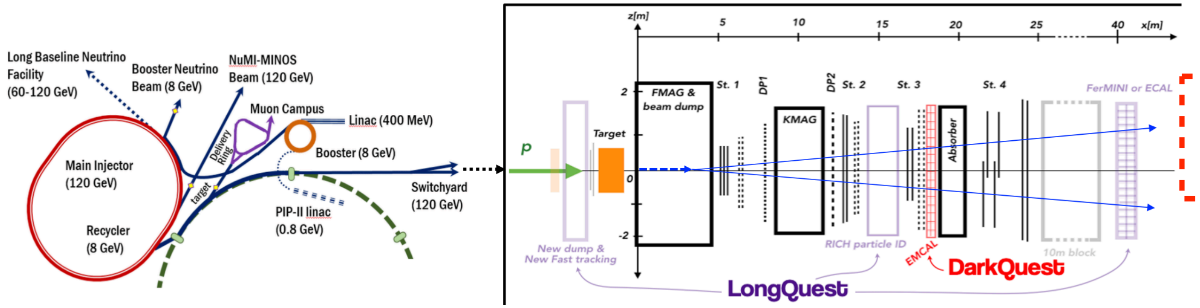
Sensitivity for m < ~0.3



800 MeV proton

FLAME at LANL

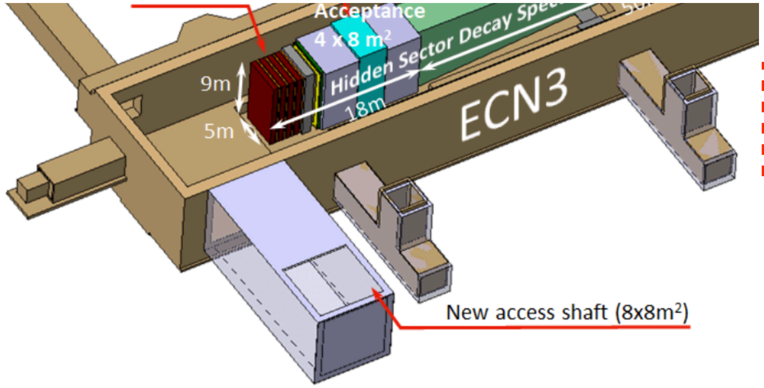
Install summer 2025



120 GeV proton

FLAME at FNAL

Plan to install early 2026



400 GeV proton

SHIP-mQ at the SPS

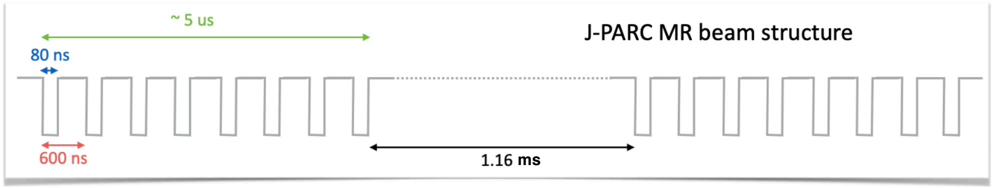
Could be installed for SHIP startup (~2030)

Designing for high-intensity

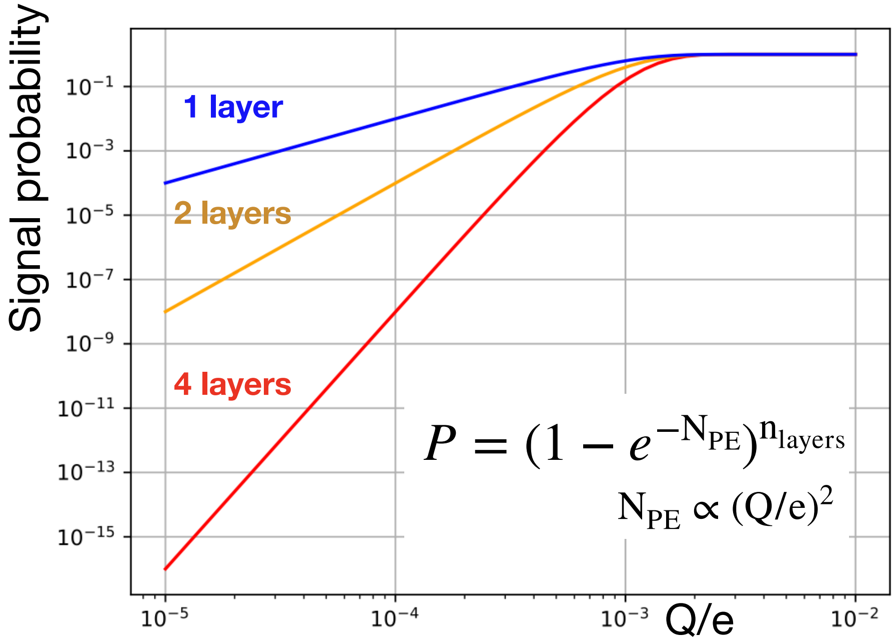
- With four layers sensitivity drops very quickly with charge **but** at LHC this design is necessary for background control

- At high intensity facilities can mitigate backgrounds by **timing with the beam** to greatly reduce live time → allows for background control with only **two layers**!

  - NB: At the LHC we have collisions every 25ns, so this doesn't help



Assuming N_{PE}=1 for Q/e = 0.001

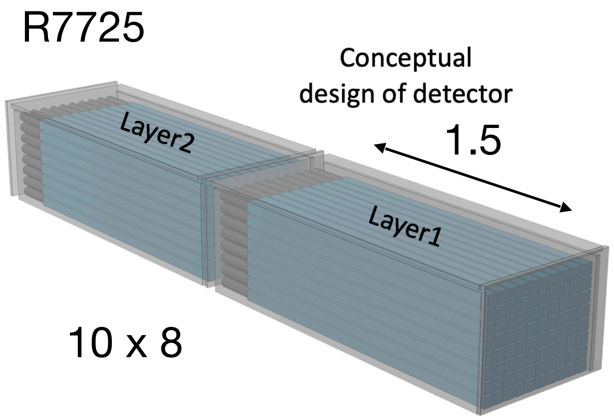


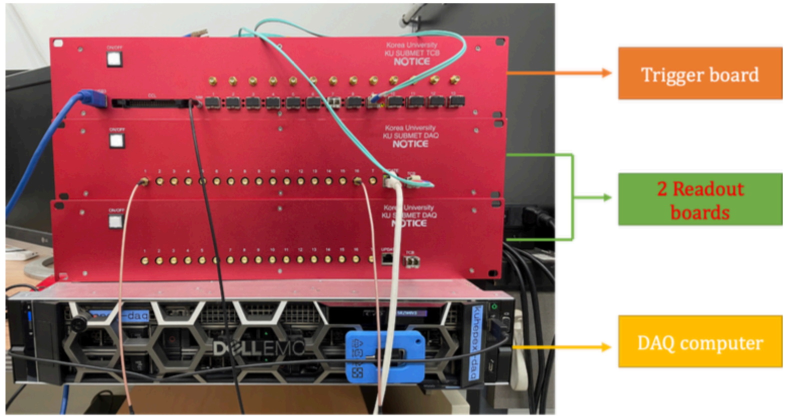
Experiment	Effective live time
FORMOSA/milliQan@LHC	~10^6/year
LANSCE-mQ@Lujan	~300s/year
SUBMET@J-PARC	~20s/year

Figures from J. Yoo

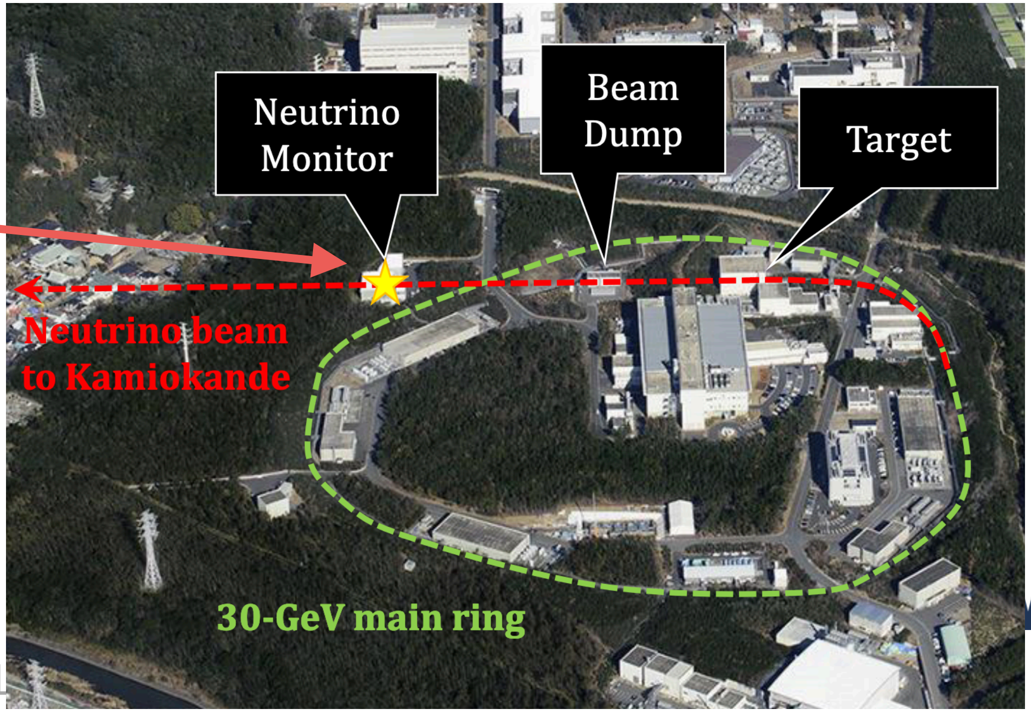
SUBMET at J-PARC

Two layers

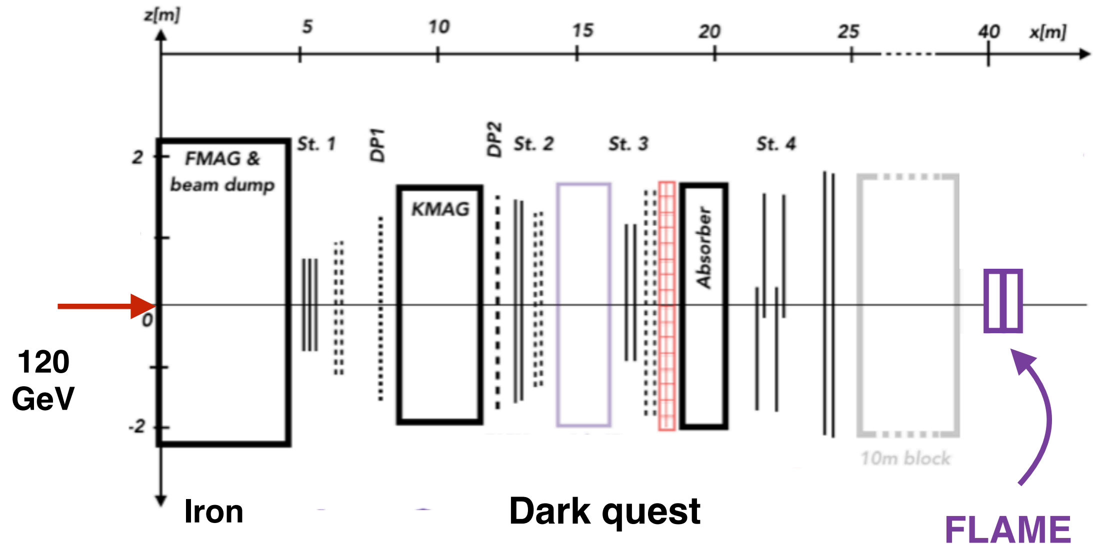


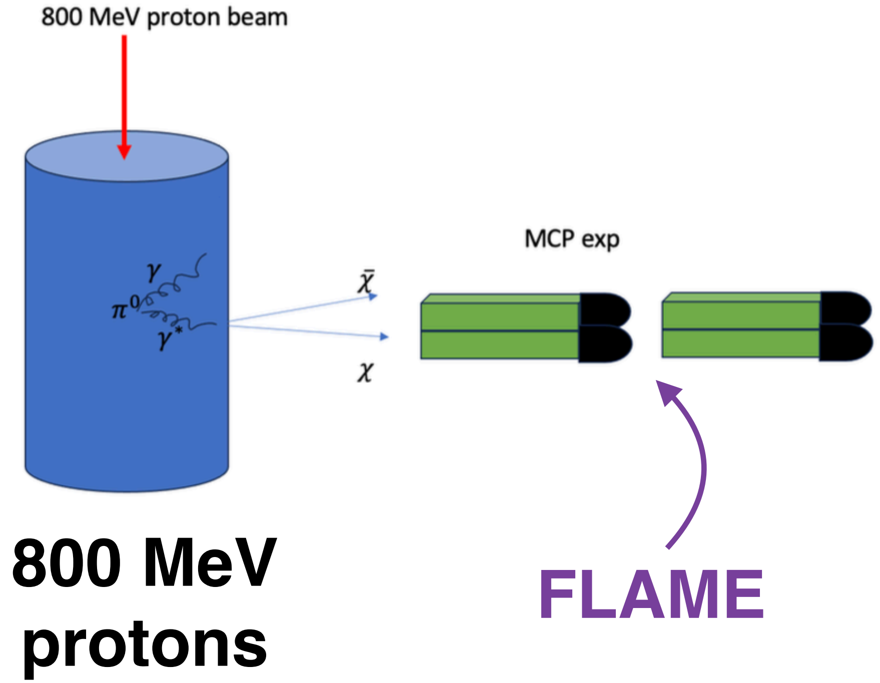


Custom readout



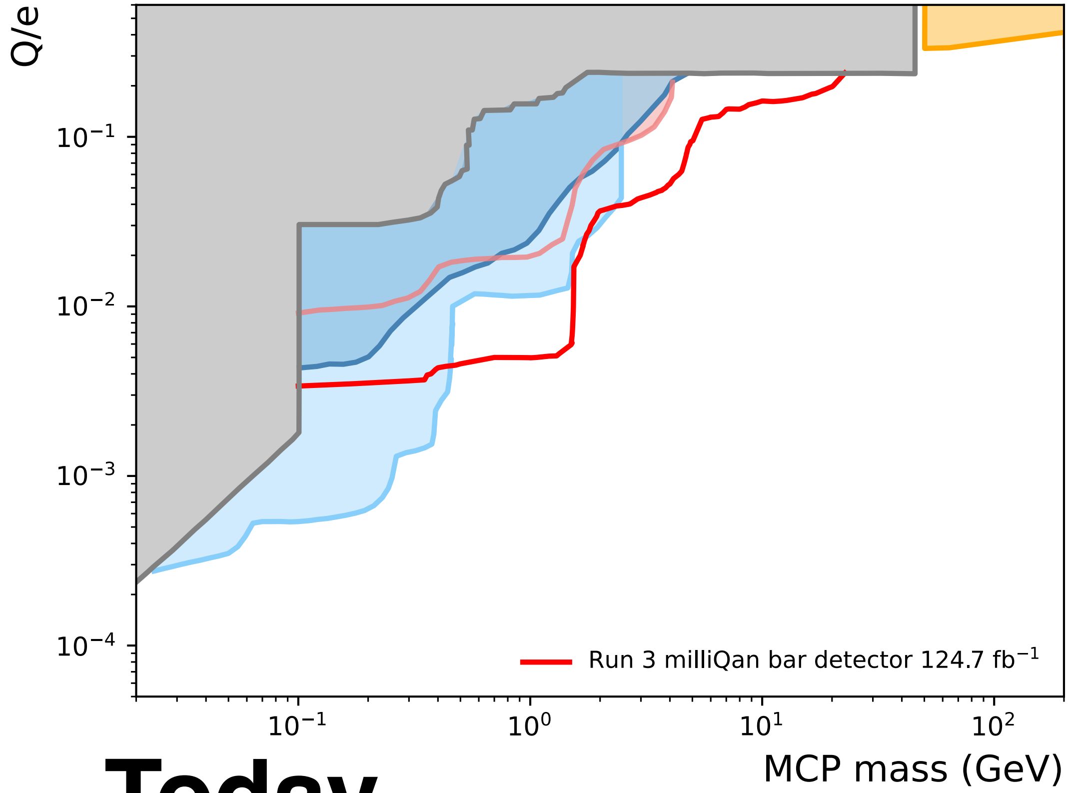
FLAME detector at LANL/FNAL





- Construct “Fermilab-Los Alamos Millicharge Experiment” (FLAME) to take data at both LANL and FNAL for wide-ranging sensitivity
- **LANL LDRD funding secured** - 32 bar detector (1.5m, R7725 PMTs) under construction now (plan to take data at LANSCE in 2025 and FNAL in 2026)
- Plan to expand and incorporate high-performance scintillator for future runs

Outlook: very exciting time for millicharged particle searches!



Today

Sources

FORMOSA: 2102.11493
SUBMET: 2007.06329
milliQan: 2104.07151
FLAME (at LANL): 2407.07142
SHIP-mQ: in preparation

- First presentation of Run 3 milliQan search provides **world leading limits**!
- **Complementary** sensitivity from multiple detectors at LHC and beyond provide **exciting** opportunities to discover unique dark sector signature!
- **SUBMET, FORMOSA demonstrator, FLAME** projects underway
- Excellent fit for **P5 recommendation** of **agile** detectors for new physics

NB: mCP production in hadronic/EM showers, and proton brem. not yet considered - coming soon!

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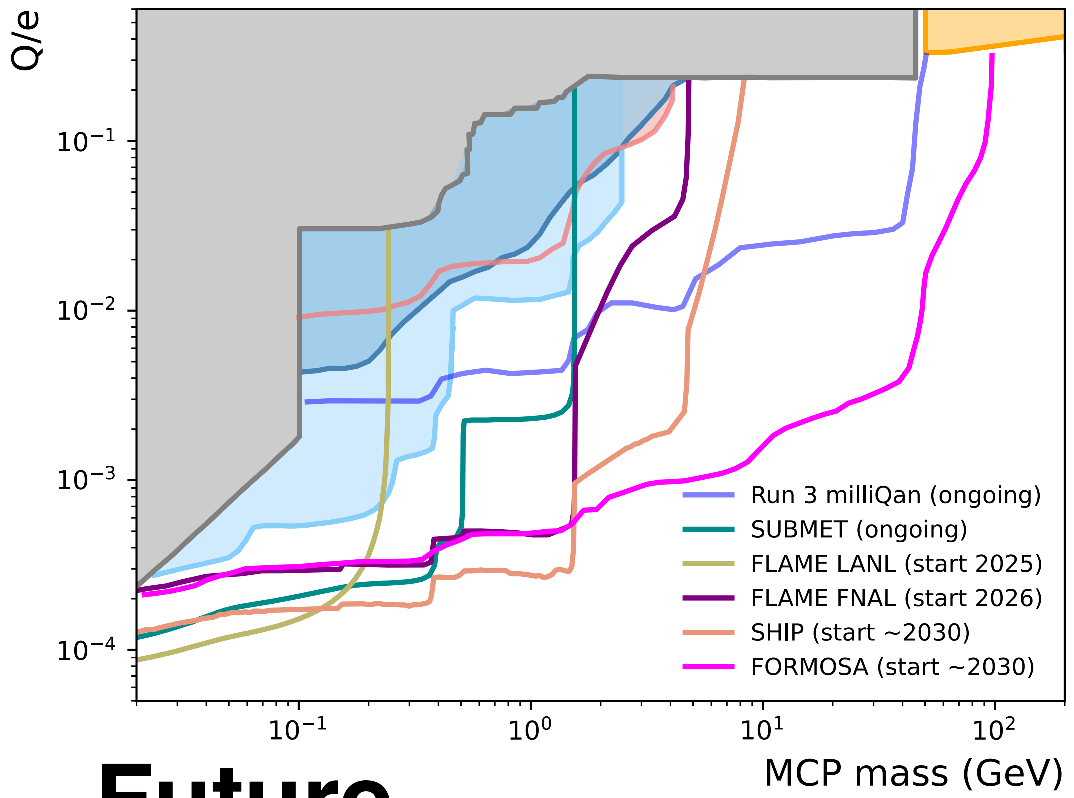

Future

Sources

FORMOSA: 2102.11493
SUBMET: 2007.06329
milliQan: 2104.07151
FLAME (at LANL): 2407.07142
SHIP-mQ: in preparation

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NB: mCP production in hadronic/EM showers, and proton brem. not yet considered - coming soon!

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The milliQan collaboration

C. Hill,
M. Joyce,
M. Carrigan

S. Alcott, K. Larina, C. Campagnari, D. Stuart, R. Schmitz,
N. Santpur, H. Mei

A. Haas,
M. Ghimire

D. Miller,
J. Heymann,
T. Du

S. Lowette
D. Vannerom

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

M. Citron,
S. Kelly,
J. Steenis,
J.S. Tafoya Vargas

M. Ezzeldine,
H. Zaraket,
M. Kamra

F. Golf
I. Reed
G. Zecchinelli

J. Brooke,
J. Goldstein

This speaker supported by funding from DOE Office of Science

The FORMOSA collaboration

Members from 9 institutions and growing!

This speaker supported by funding from DOE Office of Science

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END

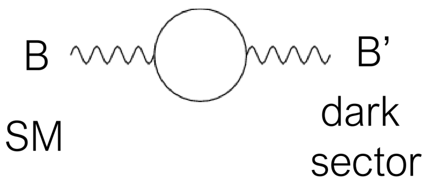
Backup

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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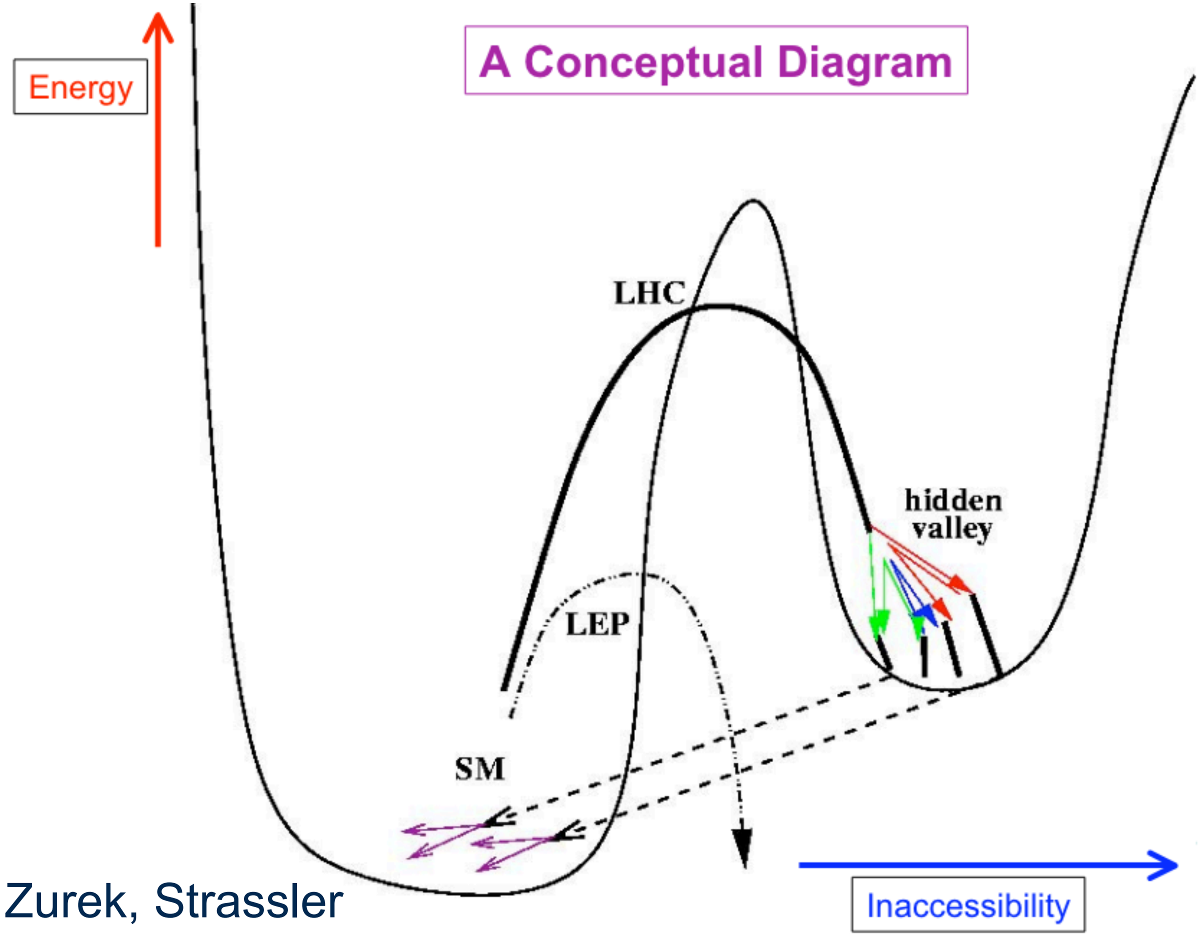
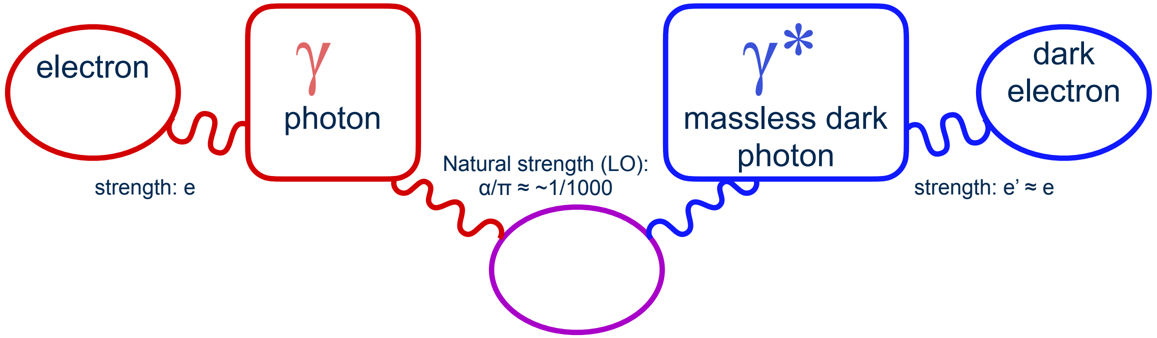
Hidden sectors: millicharged particles



Zurek, Strassler



New particle(s) charged under "dark EM" get small SM charge → **millicharged particles**

Photons and dark photons are both U(1), they can interact via **kinetic mixing**

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

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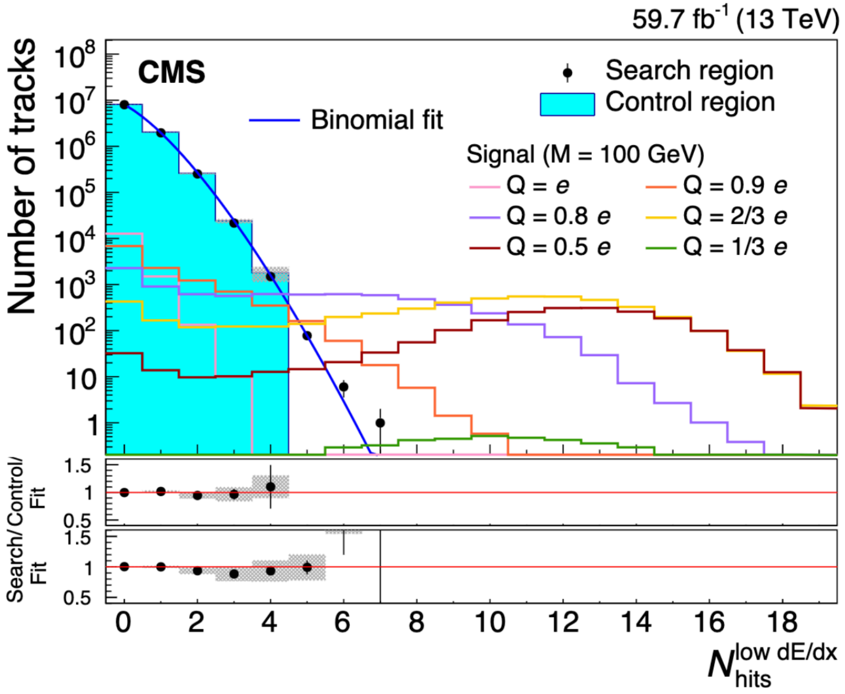
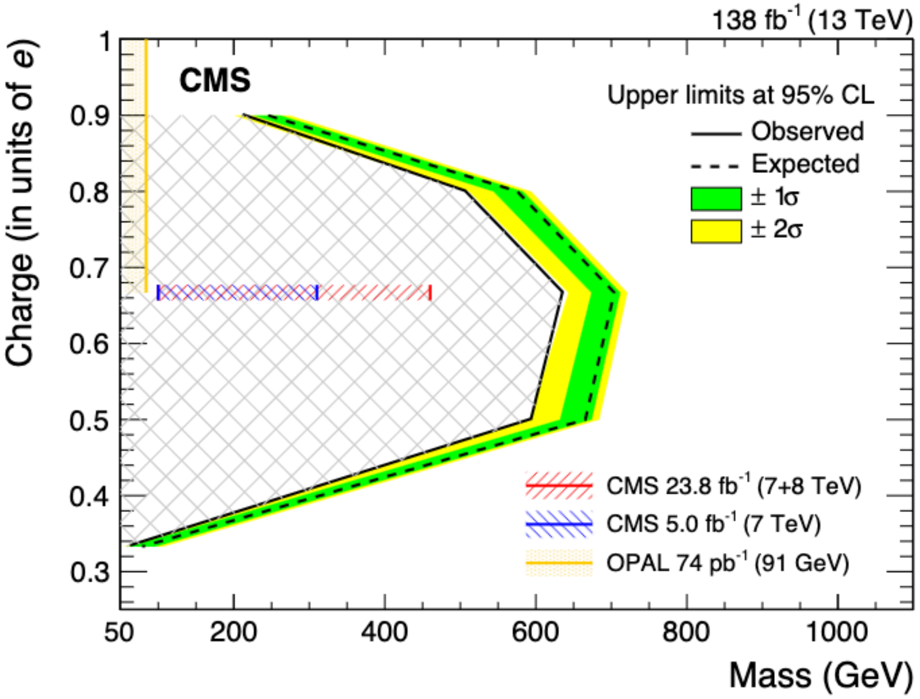
What can we do at CMS?

$$\left\langle \frac{dE}{dx} \right\rangle \propto \left(\frac{Q}{e}\right)^2$$

- Low dE/dx hits in the tracker provides **sensitivity down to Q ~ 0.3e**
- Below this not enough energy is deposited in the detector to allow reconstruction





Fractionally charged particle search
EXO-19-006

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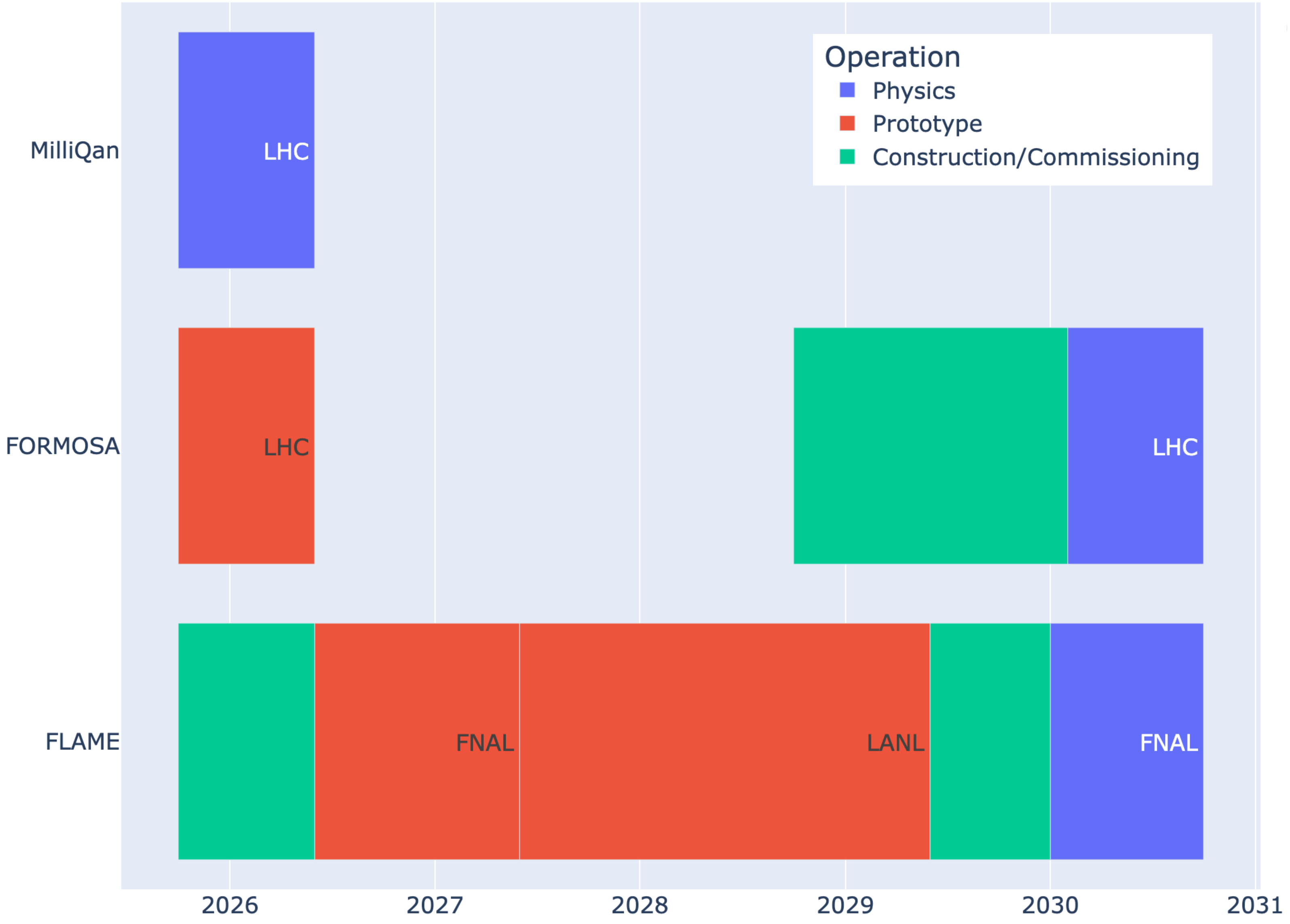
Operation schedule



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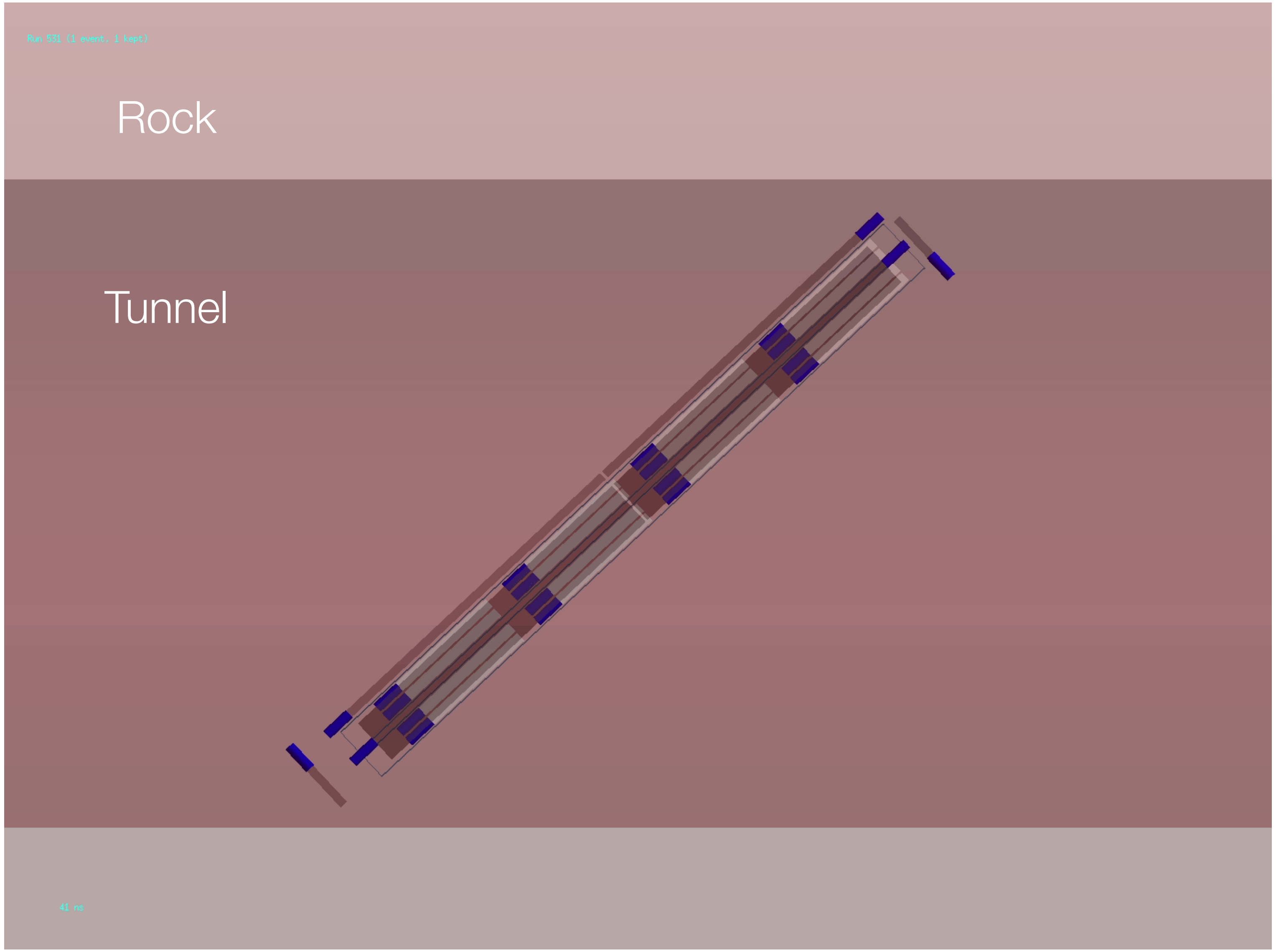
Closer look at milliQan

Closer look at milliQan

UC DAVIS

Closer look at milliQan

Millicharged particle through detector



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

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

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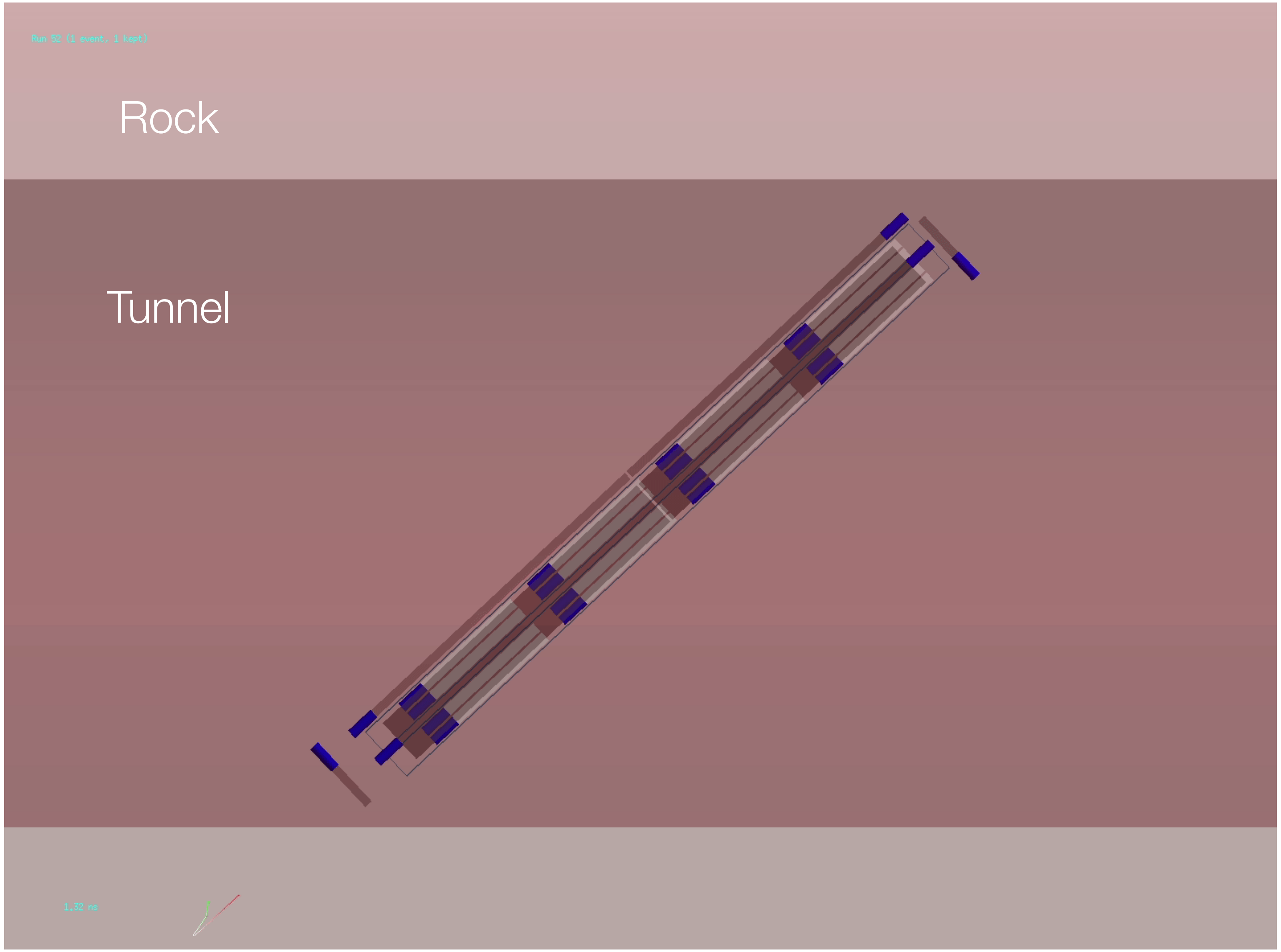
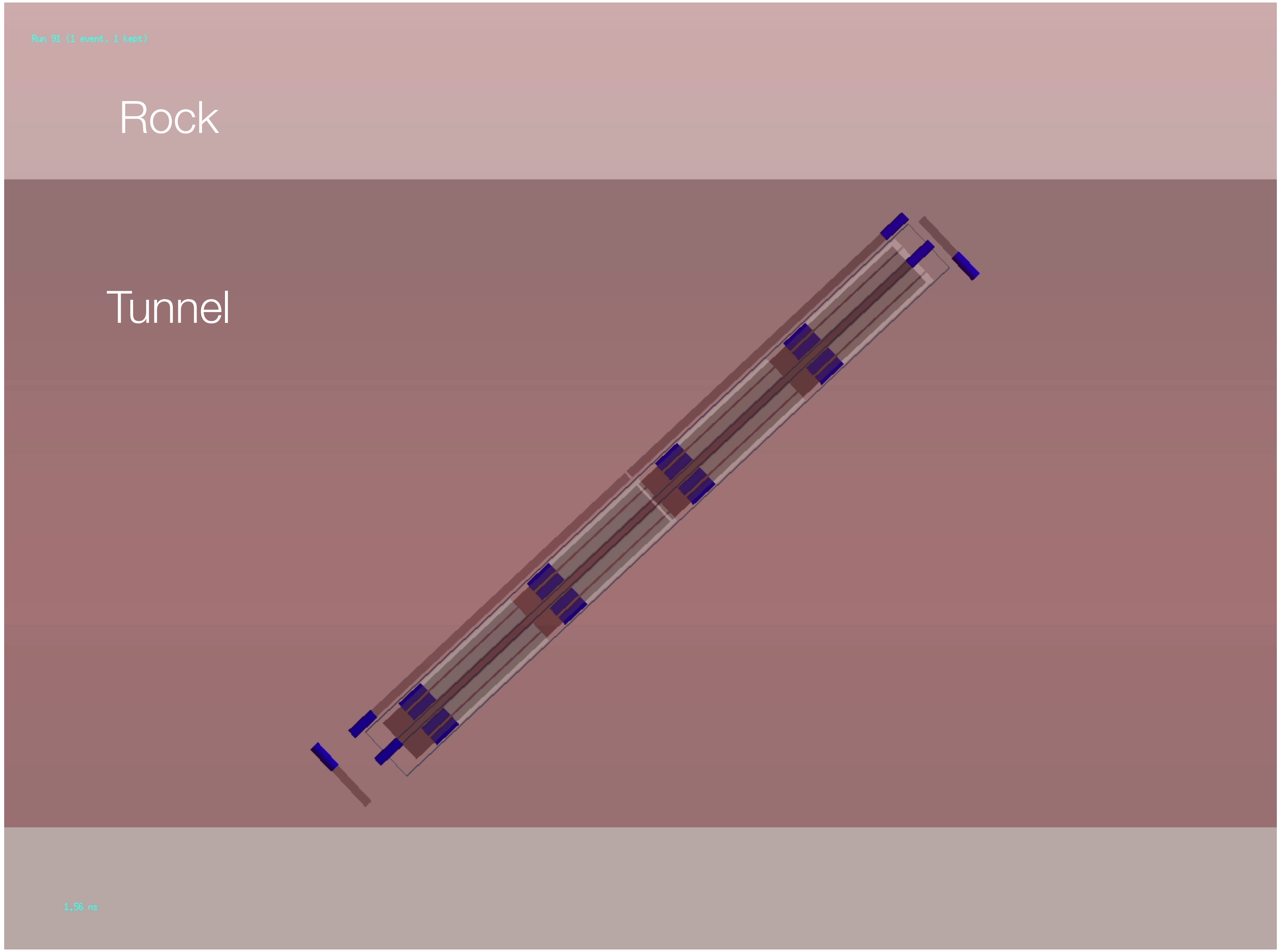
Through going muons



- 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

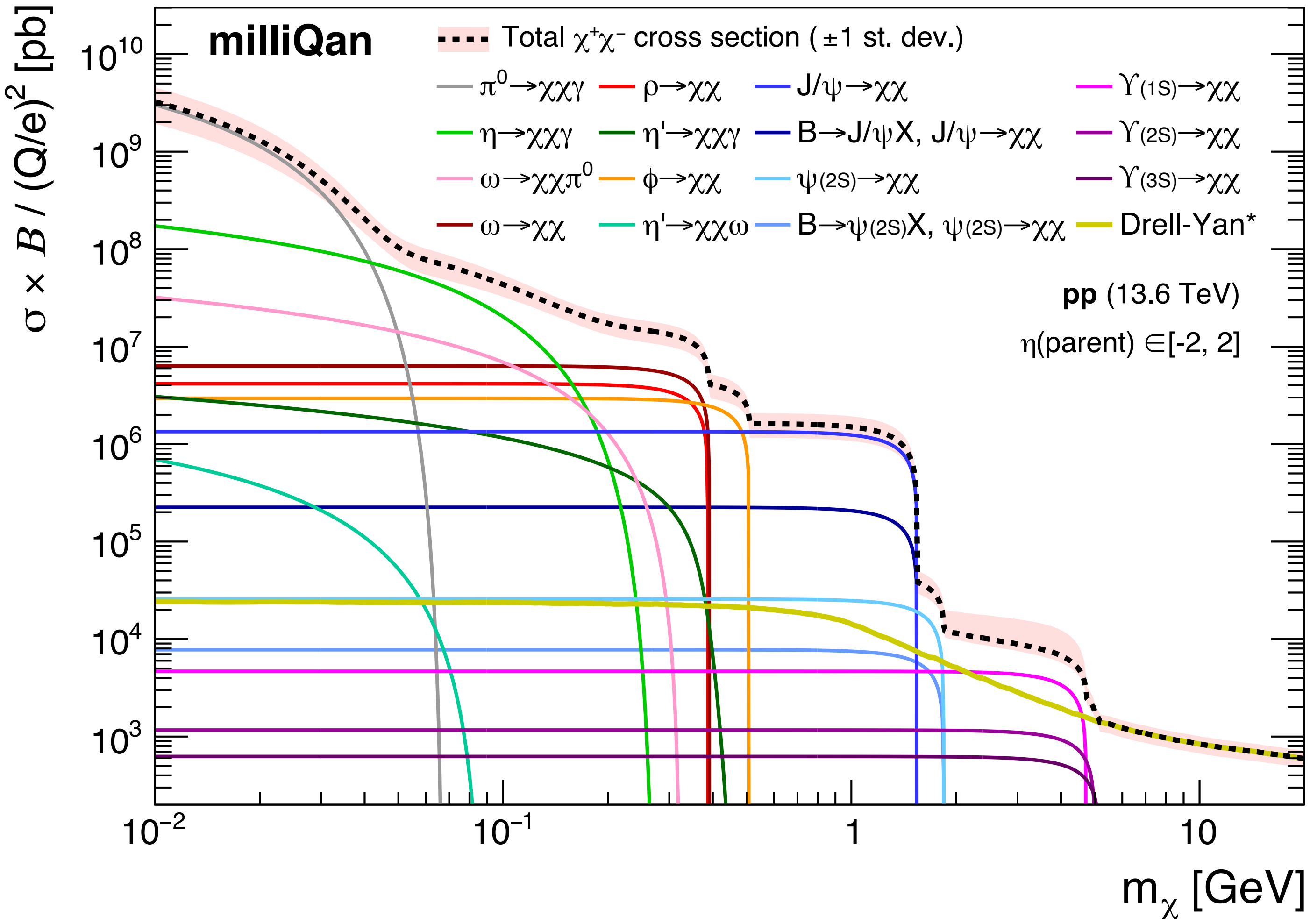
Background from cosmic ray showers



- 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

Signal simulation

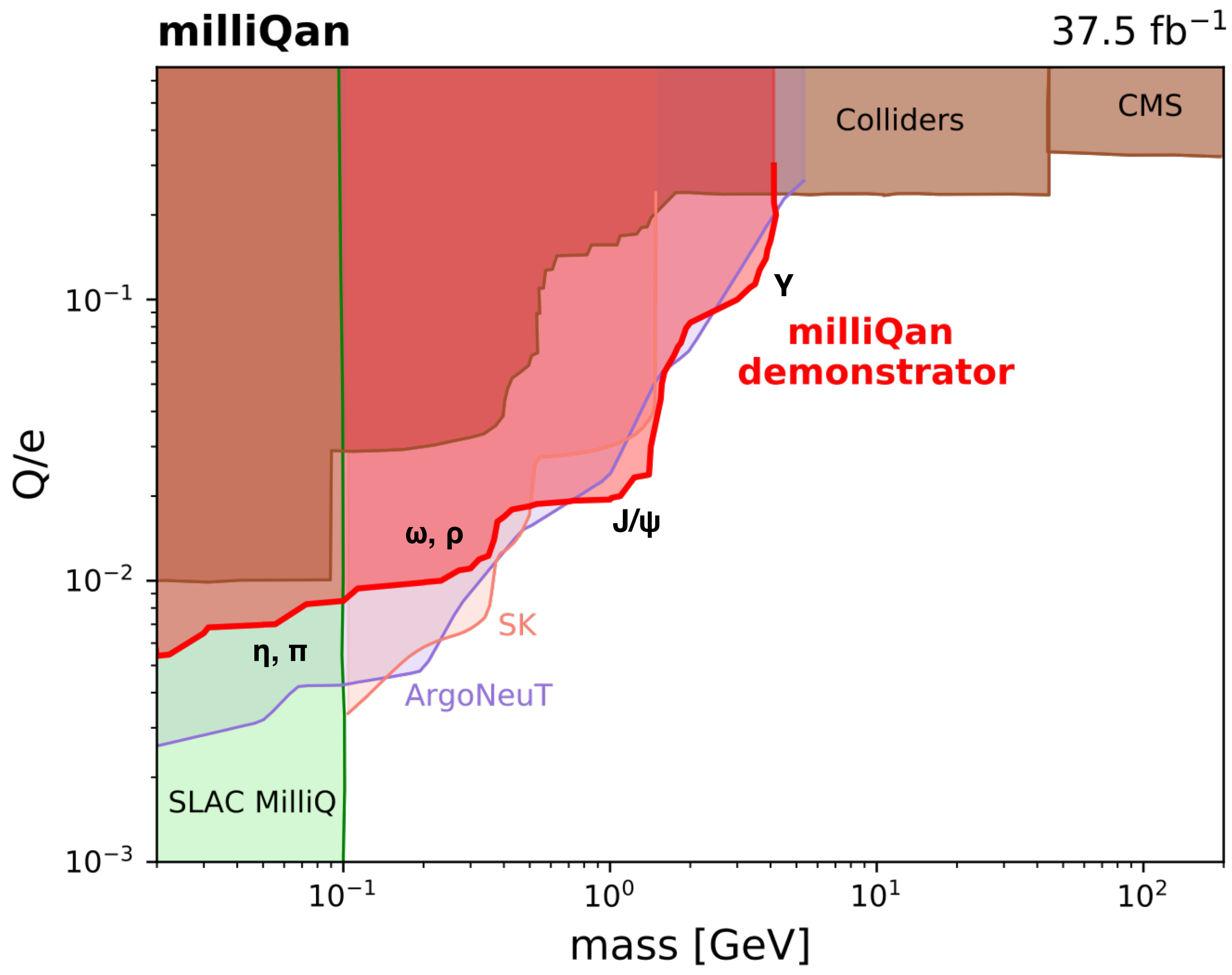


Signal simulation comprised of a wide range of DY/meson producction channels

The milliQan demonstrator

- **First** search for mCPs at a hadron collider achieves **new sensitivity** with small demonstrator $37.5\ \text{fb}^{-1}$ of LHC Run 2 data
- **Three layers** of 3x2 scintillator bar arrays
- Provides **quantitative** understanding of backgrounds and detector performance
- **Fully validated simulation** of detector and backgrounds

→ **Works as a guide future detectors!**



Demonstrator results published in PRD: PhysRevD.102.032002

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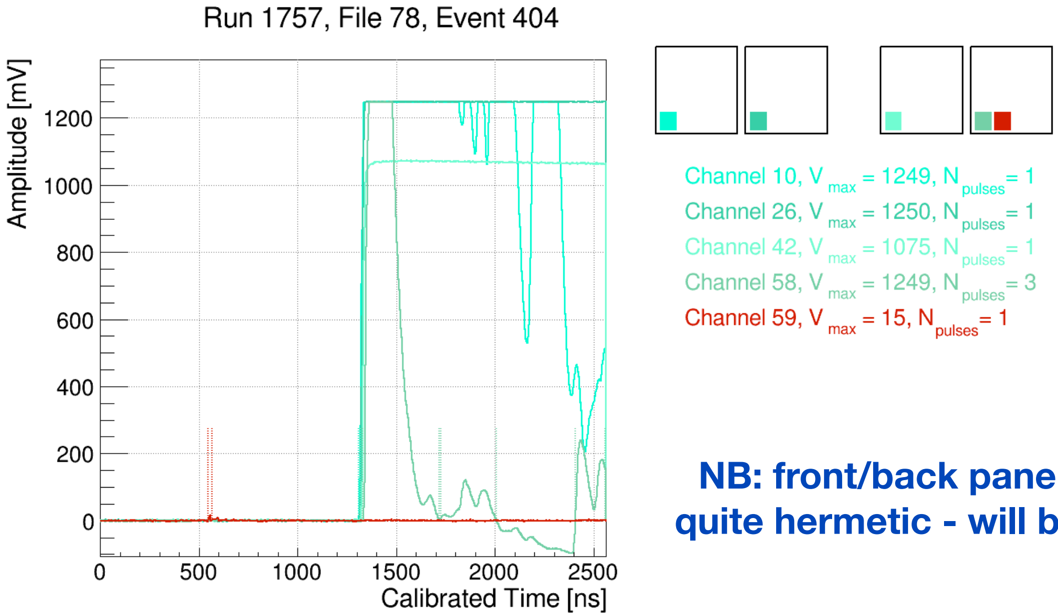
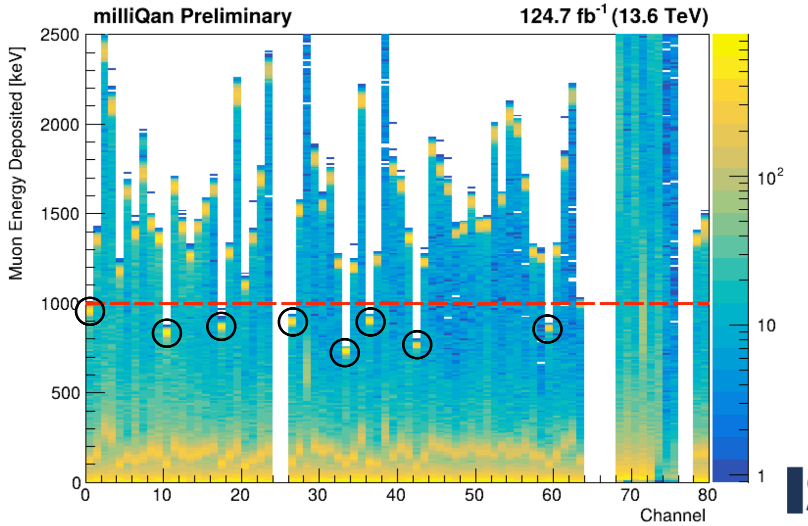
Muon event that initially leaked into SR1

- 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: $nPE_{max}^{Panel} < 70$	—	—	—	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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Full background rejection

Selection	Beam-Off	Beam-On	m=0.1 q=0.004	m=1.0 q=0.008
Total Events	1002647.0 (100.0)	790776.0 (100.0)	324.0 (88.0)	61.26 (88.0)
Digitizers Synchronized	1002617.0 (100.0)	790772.0 (100.0)	324.0 (88.0)	61.26 (88.0)
Pickup	1002617.0 (100.0)	790772.0 (100.0)	324.0 (88.0)	61.26 (88.0)
Dark Rate	1002612.0 (100.0)	790772.0 (100.0)	324.0 (88.0)	61.26 (88.0)
$\leq$ 6 Bars	669318.0 (66.76)	506770.0 (64.09)	324.0 (88.0)	61.26 (88.0)
First Pulse	669318.0 (66.76)	506770.0 (64.09)	324.0 (88.0)	61.26 (88.0)
Trigger Window	668781.0 (66.7)	506417.0 (64.04)	323.89 (87.97)	61.26 (88.0)
Top/Side Panel Veto	377523.0 (37.65)	287811.0 (36.4)	266.91 (72.49)	38.91 (55.9)
4 Layers	2360.0 (0.24)	3369.0 (0.43)	11.97 (3.25)	19.34 (27.78)
$\leq$ 4 Bars	921.0 (0.09)	985.0 (0.12)	11.65 (3.16)	19.34 (27.78)
Noise	921.0 (0.09)	985.0 (0.12)	11.65 (3.16)	19.34 (27.78)
Front/Back Panel Veto	908.0 (0.09)	744.0 (0.09)	11.43 (3.1)	16.77 (24.09)
Energy $\leq$ 1000 keV	908.0 (0.09)	739.0 (0.09)	11.43 (3.1)	16.77 (24.09)
Energy Max/Min $\leq$ 10(5)	258.0 (0.03)	215.0 (0.03)	10.09 (2.74)	14.32 (20.57)
Straight Line	7.0 (0.0)	3.0 (0.0)	9.22 (2.5)	14.27 (20.5)
Δ T(max-min) $\leq$ 20 ns	0.0 (0.0)	0.0 (0.0)	8.68 (2.36)	14.13 (20.3)

SR1

Selection	Beam-Off	Beam-On	m=1.7 q=0.03	m=10.0 q=0.2
Total Events	1002647.0 (100.0)	790776.0 (100.0)	27.0 (88.0)	37.24 (87.99)
Digitizers Synchronized	1002617.0 (100.0)	790772.0 (100.0)	27.0 (88.0)	37.24 (87.99)
Pickup	1002617.0 (100.0)	790772.0 (100.0)	27.0 (88.0)	37.24 (87.99)
Noise	1002085.0 (99.94)	790681.0 (99.99)	27.0 (88.0)	37.24 (87.99)
Dark Rate	1001107.0 (99.85)	790566.0 (99.97)	27.0 (88.0)	37.24 (87.99)
First Pulse	1001107.0 (99.85)	790566.0 (99.97)	27.0 (88.0)	37.24 (87.99)
Trigger Window	998734.0 (99.61)	789542.0 (99.84)	26.99 (87.96)	37.24 (87.99)
Top/Side Panel Veto	453277.0 (45.21)	347159.0 (43.9)	16.61 (54.13)	22.71 (53.66)
4 Layers	4570.0 (0.46)	9150.0 (1.16)	7.65 (24.93)	9.54 (22.54)
Front/Back Panel Required	686.0 (0.07)	5901.0 (0.75)	5.92 (19.29)	9.0 (21.26)
Energy Max/Min $\leq$ 10(5)	105.0 (0.01)	1482.0 (0.19)	5.86 (19.1)	8.95 (21.15)
Straight Line	63.0 (0.01)	1352.0 (0.17)	5.81 (18.94)	8.89 (21.0)
Δ T(max-min) $\leq$ 20 ns	51.0 (0.01)	1299.0 (0.16)	5.78 (18.84)	8.15 (19.26)
$\leq$ 4 Bars	1.0 (0.0)	83.0 (0.01)	5.77 (18.81)	7.3 (17.25)
nPE_{max}Front/Back Panel < 70	0.0 (0.0)	2.0 (0.0)	5.77 (18.81)	6.99 (16.52)

SR2

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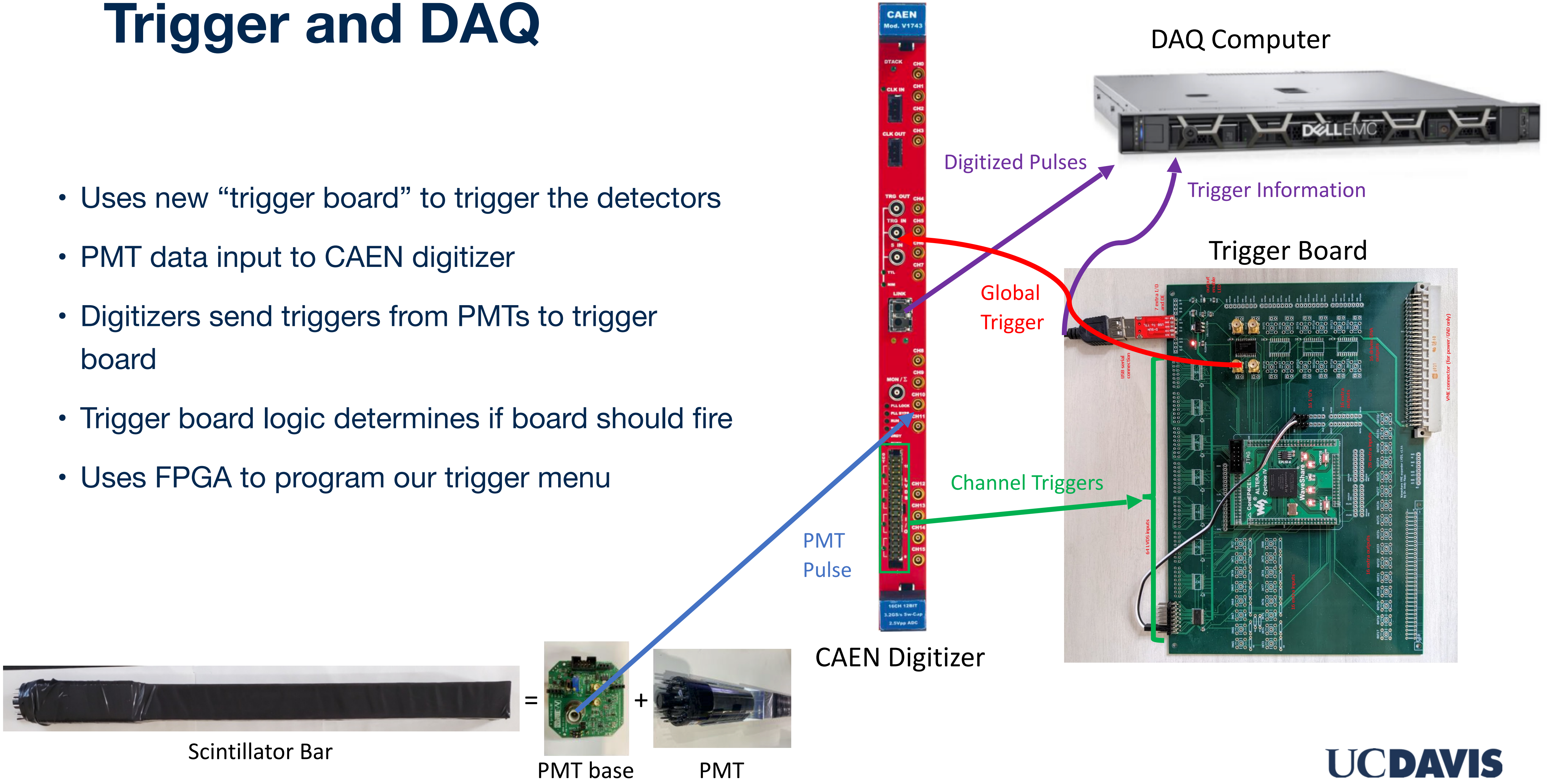
Trigger and DAQ

- 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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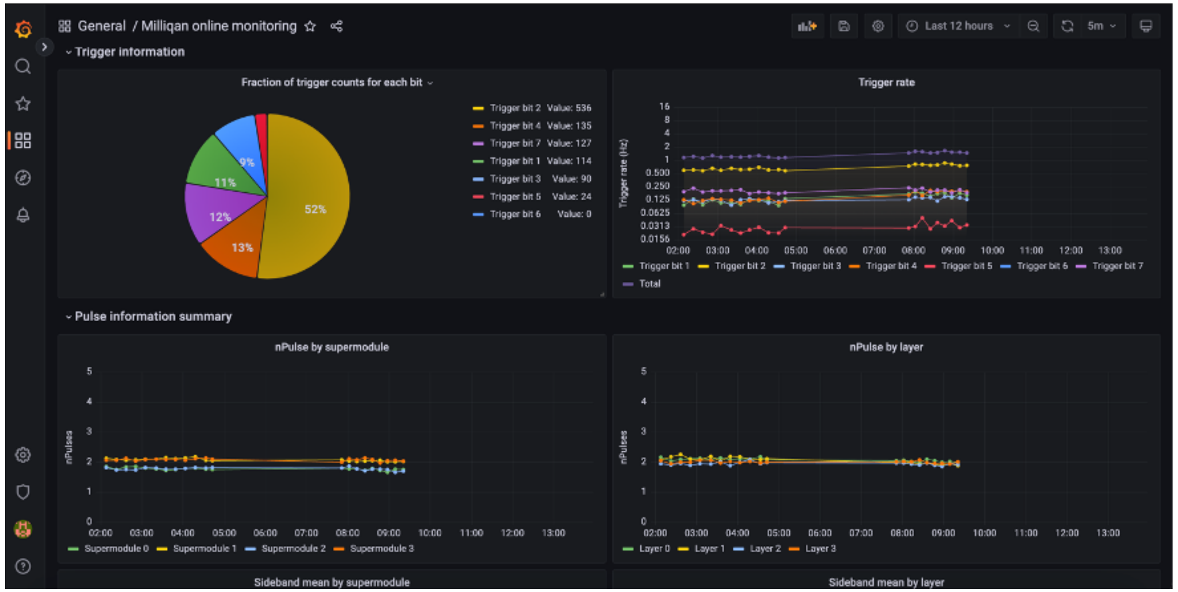
DAQ & Trigger Monitoring

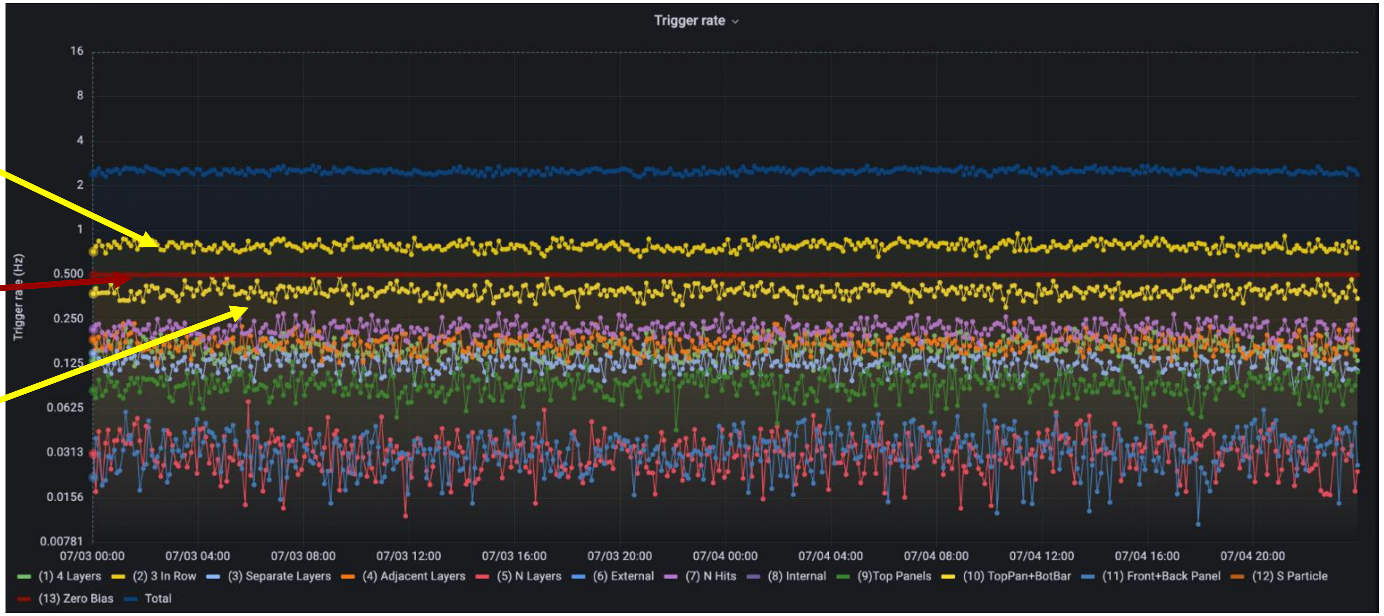
- Web-based interfaces/DBs to run & monitor the detector
  - Stable continuous data taking since June 1st 2023



dominant trigger still 3 in a row

zero bias 0.5Hz

cosmics top+bot



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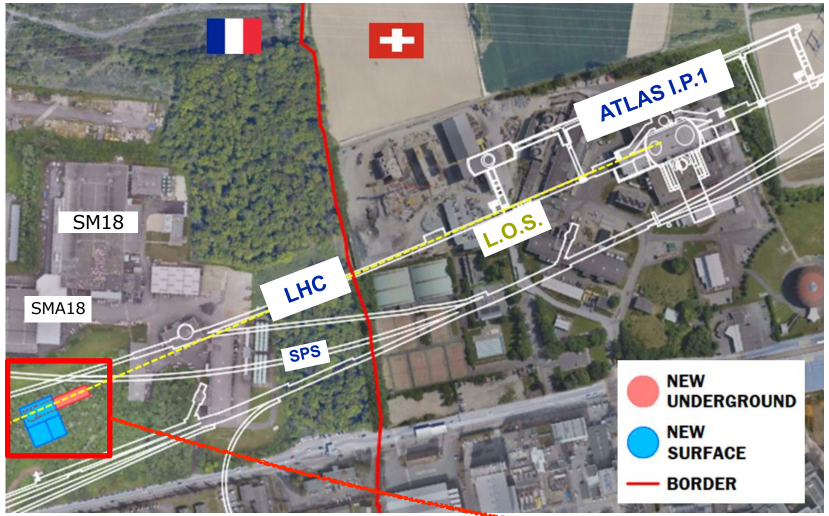
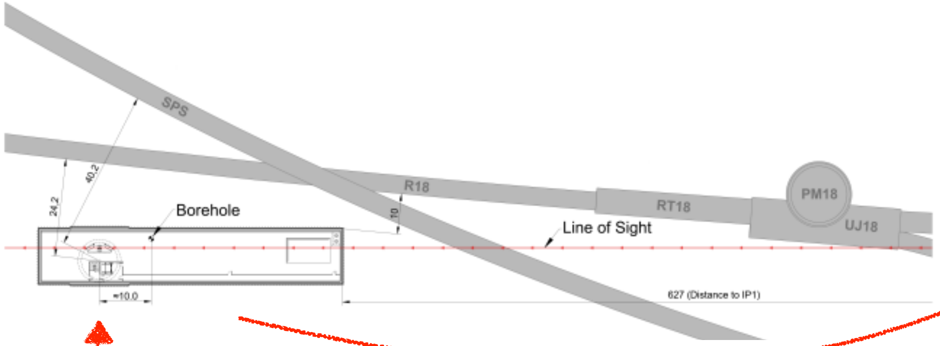
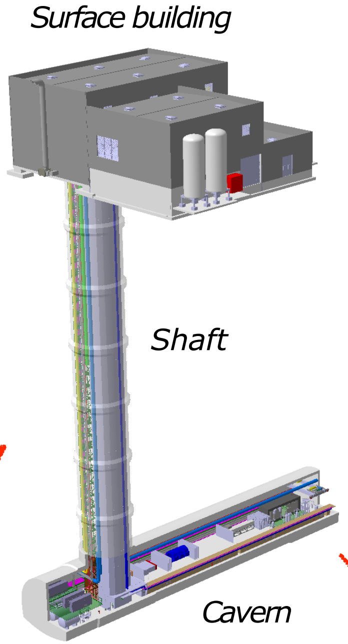
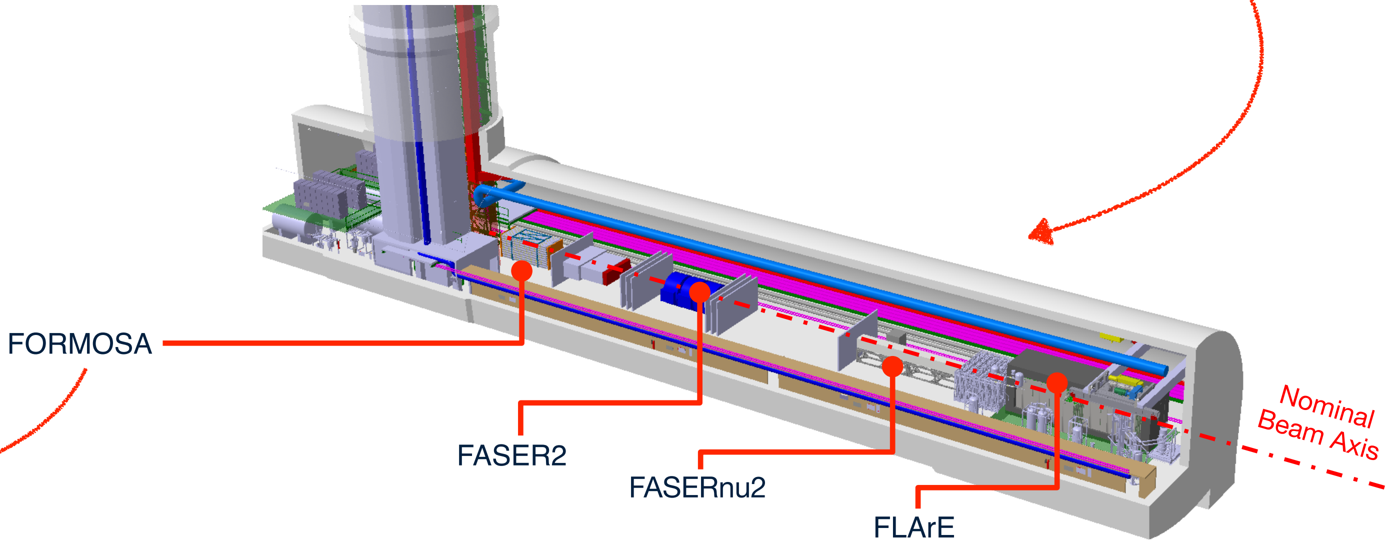
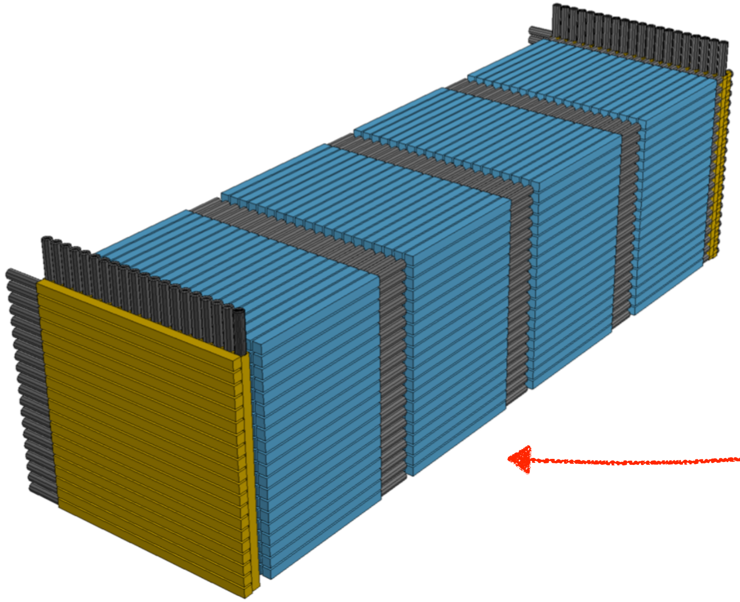
FORMOSA at the FPF







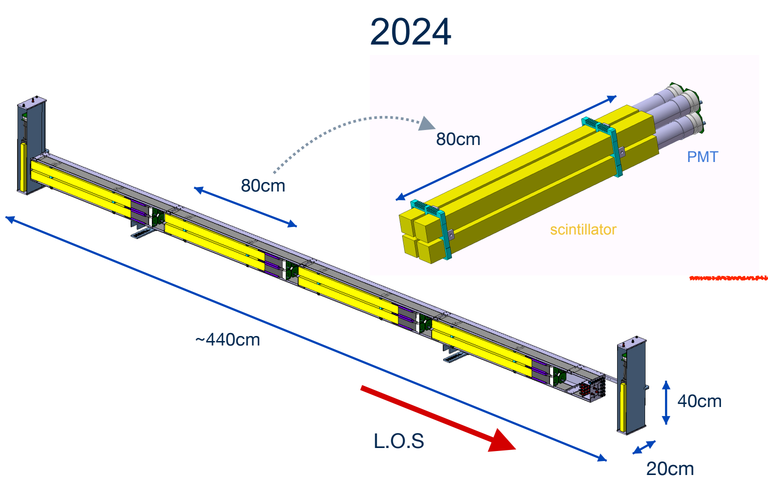


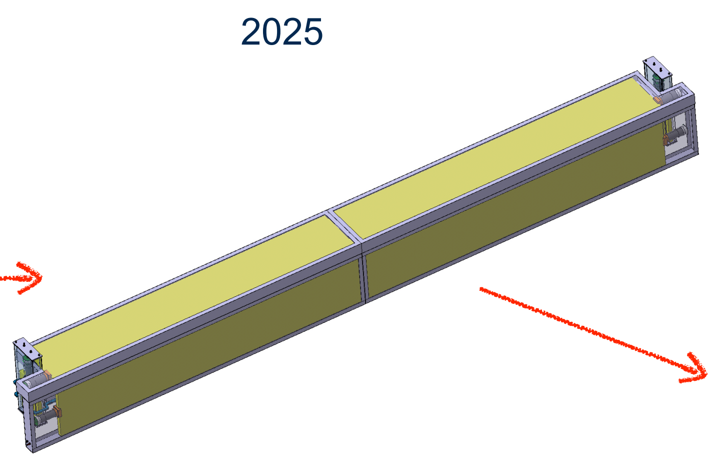


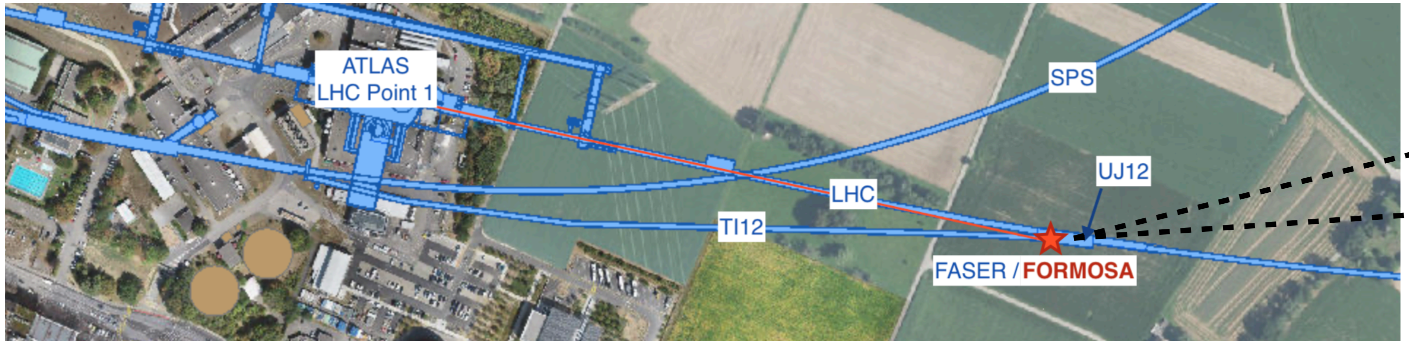
The FORMOSA demonstrator

Proof of concept: collecting data and validating design/DAQs through Run 3

Design evolving to test new technologies and adapt to UJ12's environment







CeBr3 module

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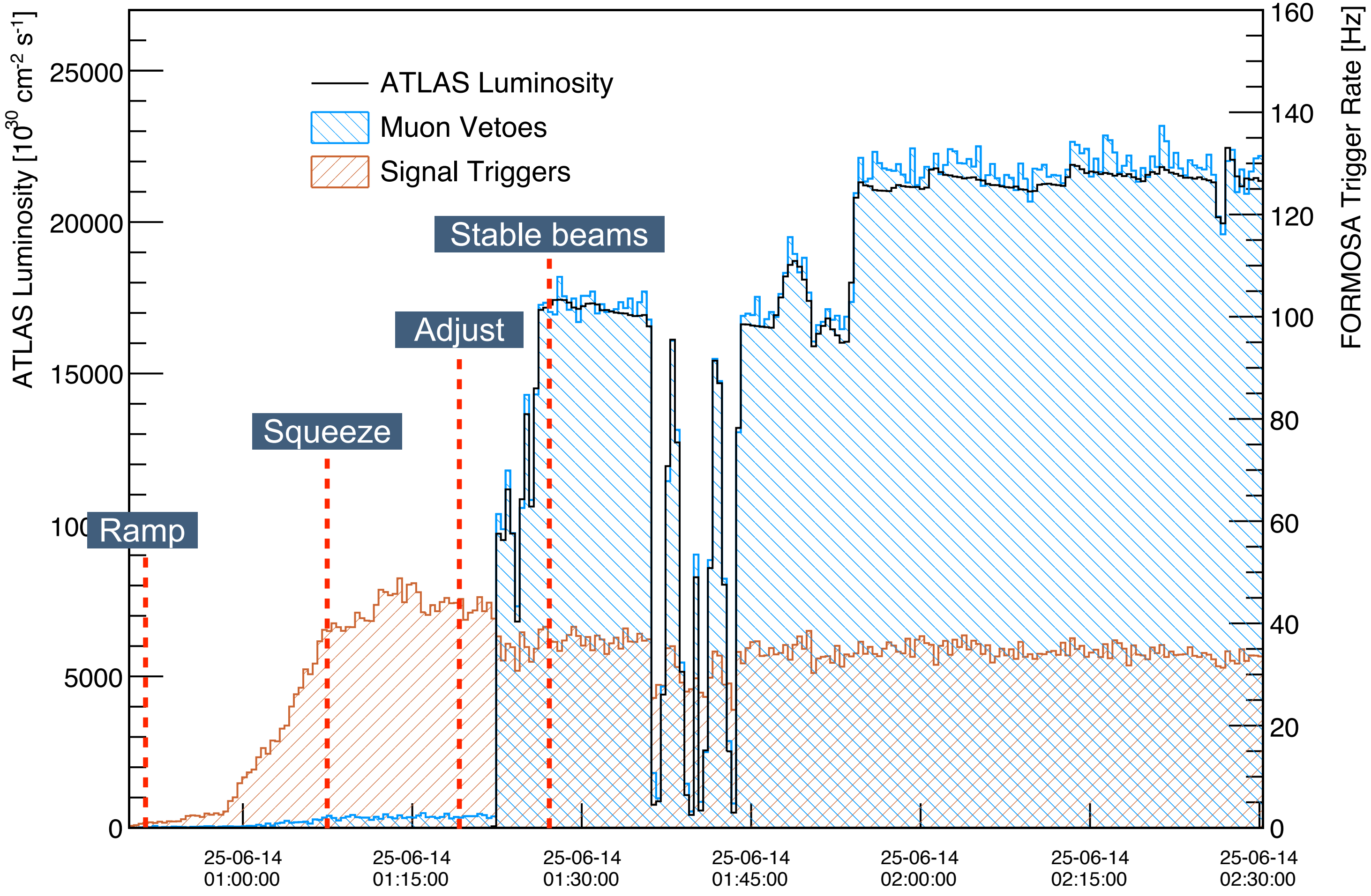
DAQ validation



Data from the 14th of June 2025

Signal triggers stably collecting data

Muons very effectively vetoed!

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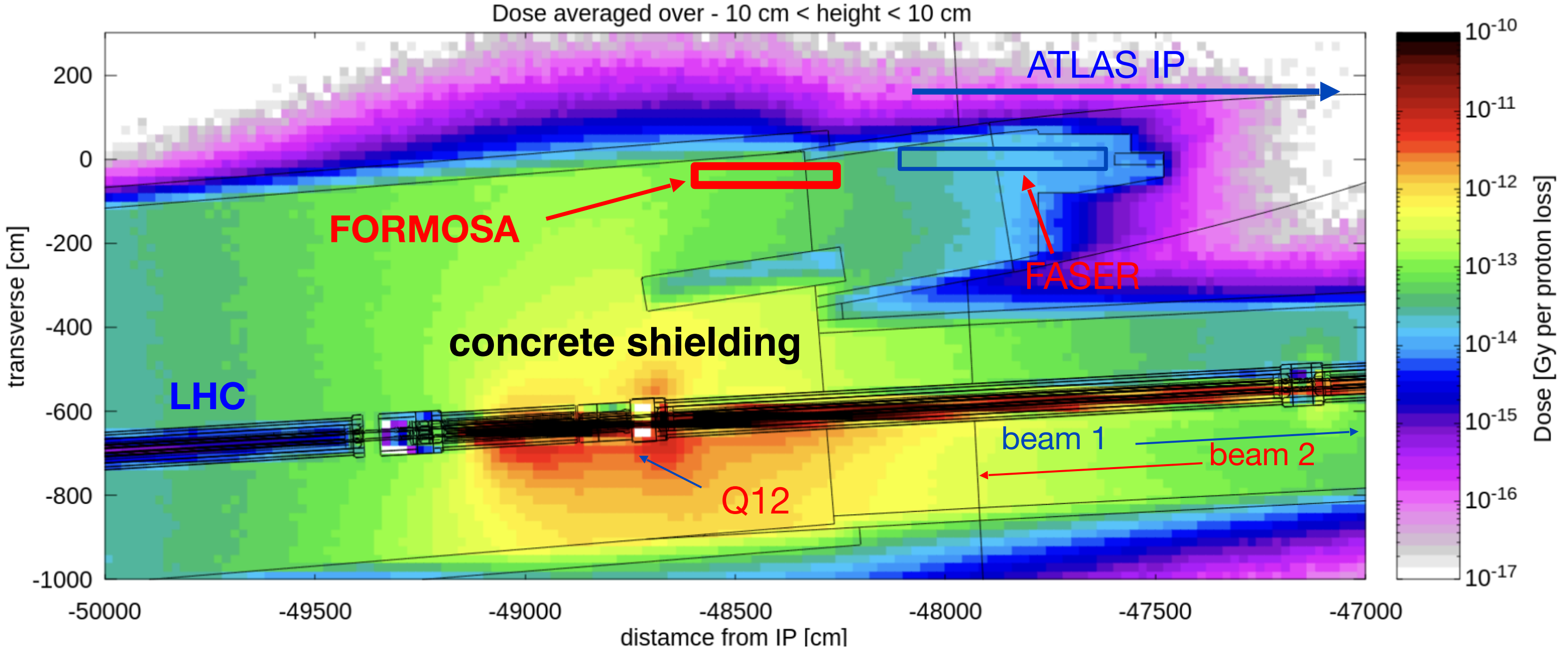
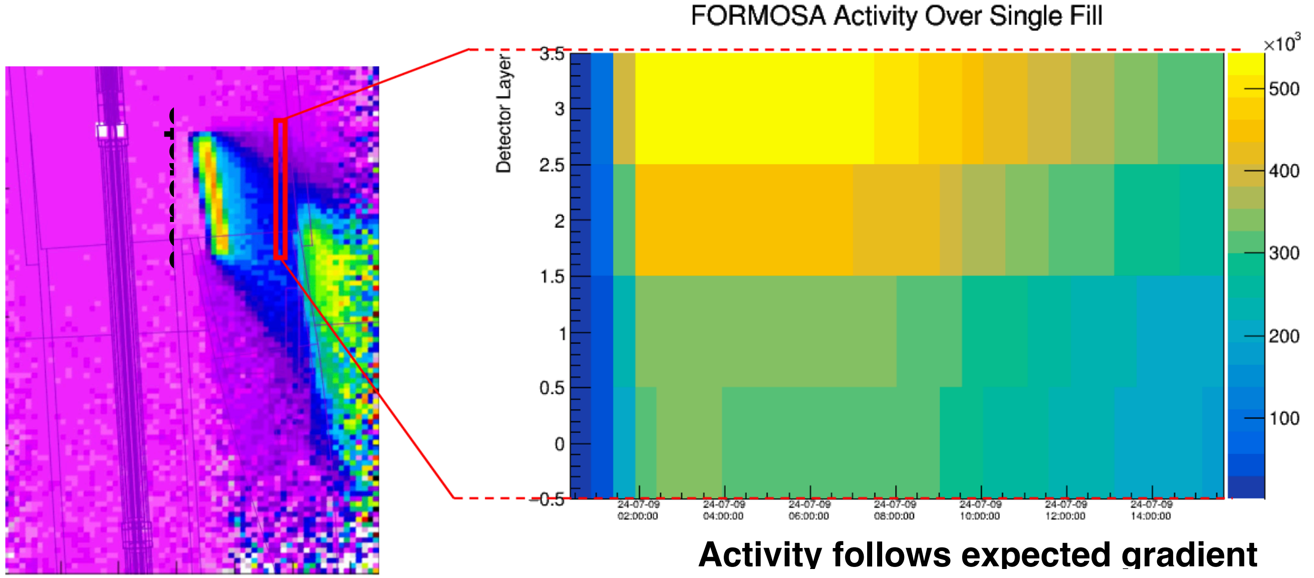
Beam backgrounds



- Initially beam backgrounds (not present at FPF) overwhelmed our trigger

- Addressed by adding **side panels** + vetoes on multiple bars hit in each layer



Activity follows expected gradient