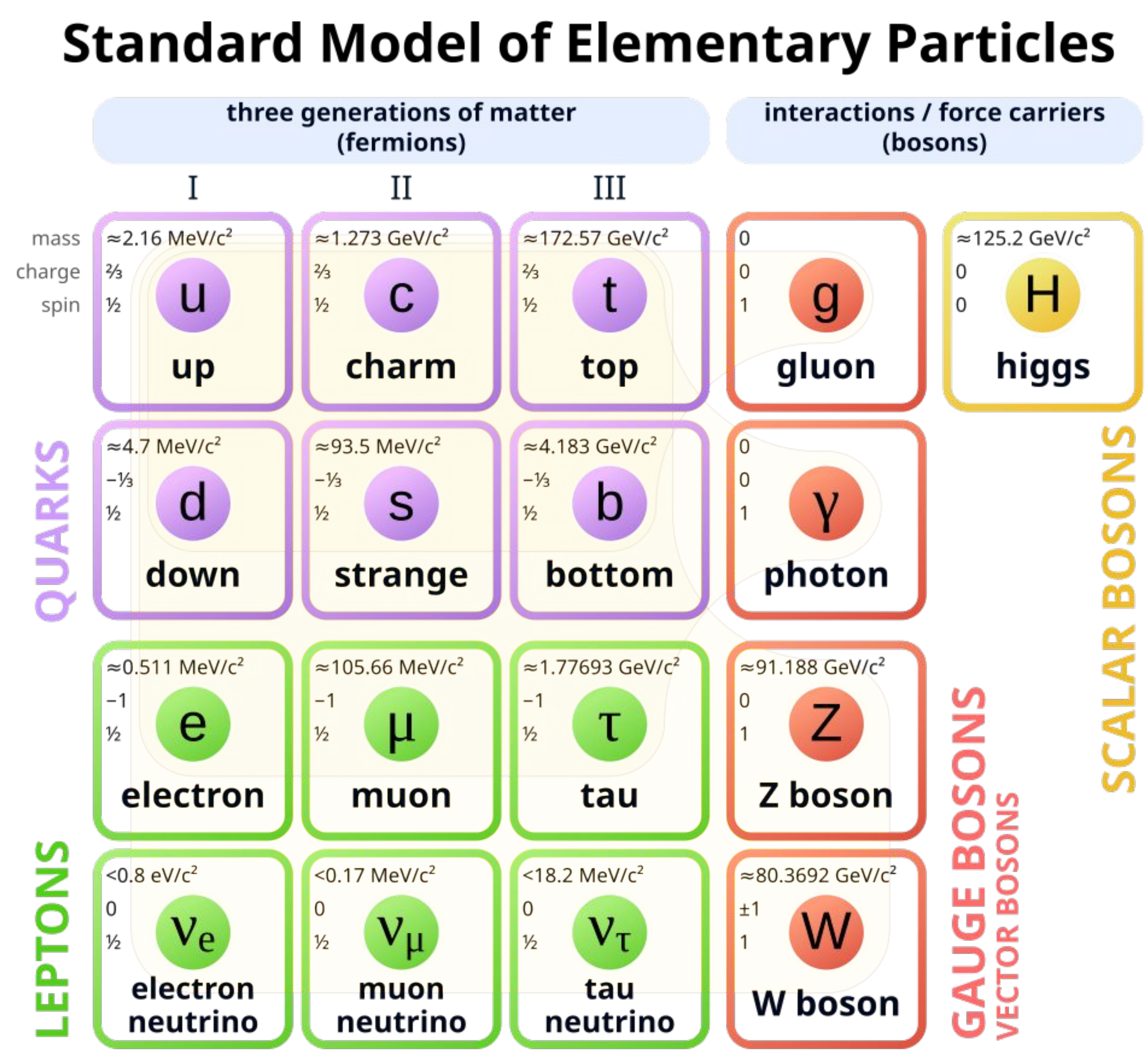
First Physics Results from MilliQan with LHC Run3 data

29/09/2025

Giacomo Zecchinelli

Introduction

The Standard Model of particle physics is the best description of the visible universe…



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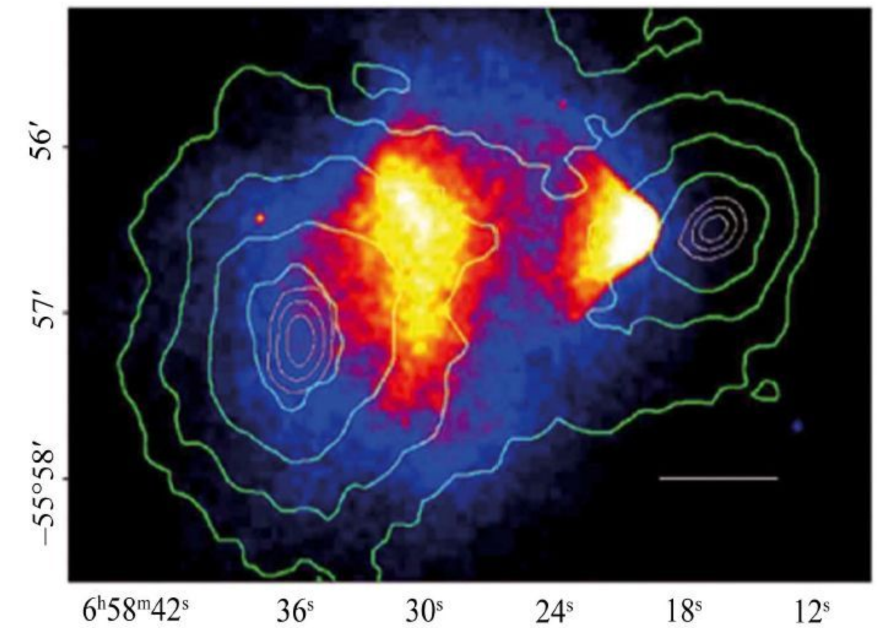
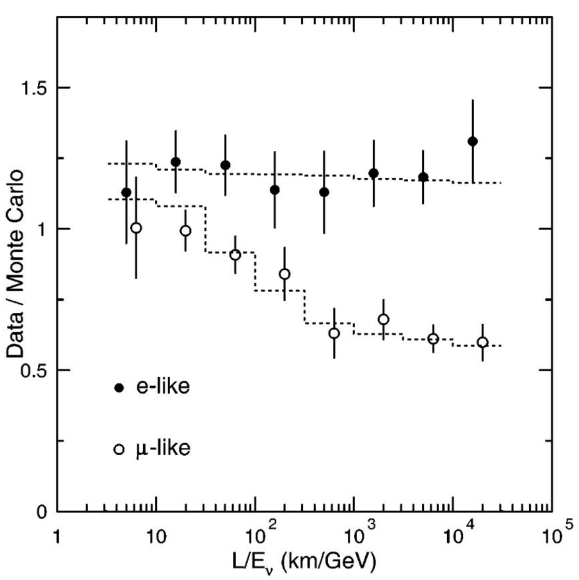
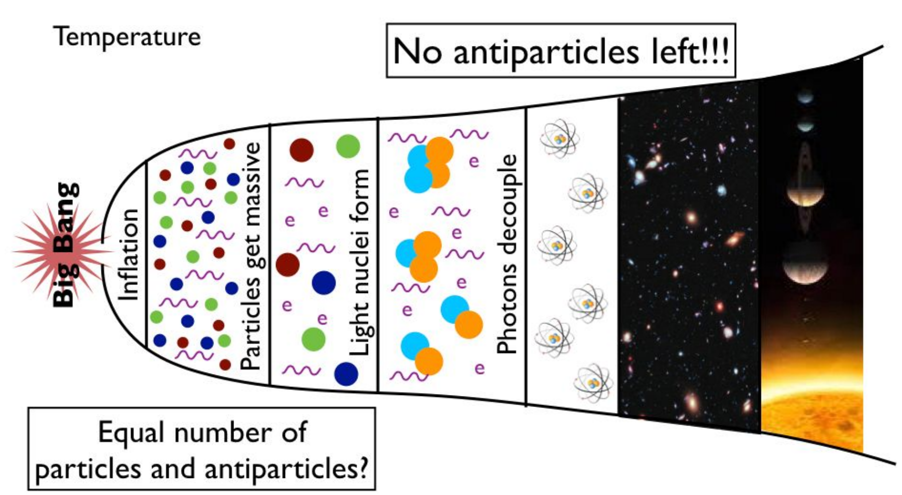
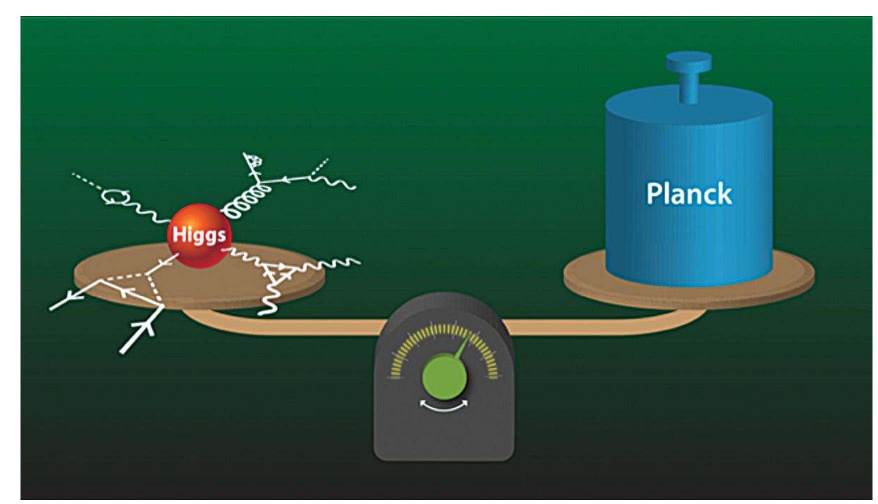
… yet several questions are still to be answered:

- What is Dark Matter made of ?
- Why there is more matter then antimatter ?
- Why neutrinos have mass?
- Why the Higgs bosons is so light?









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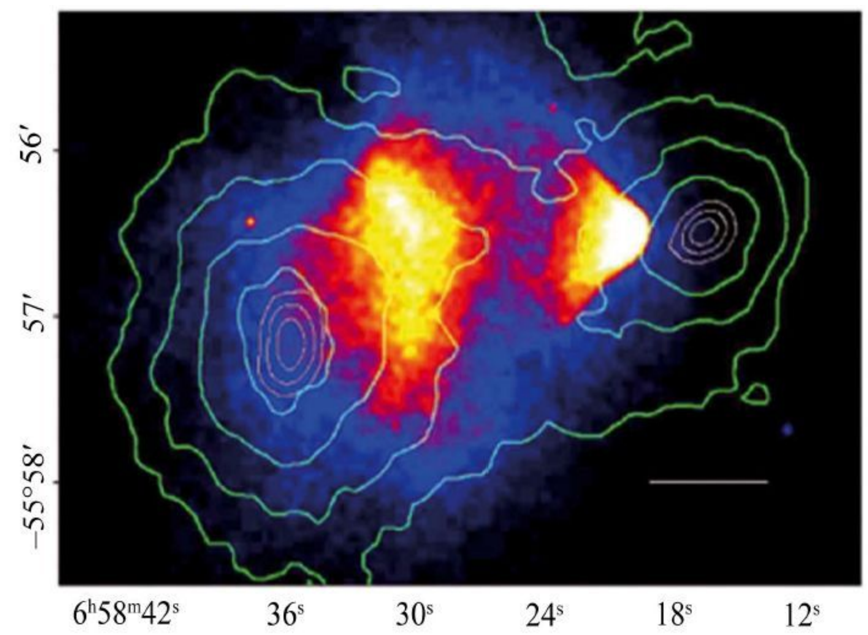
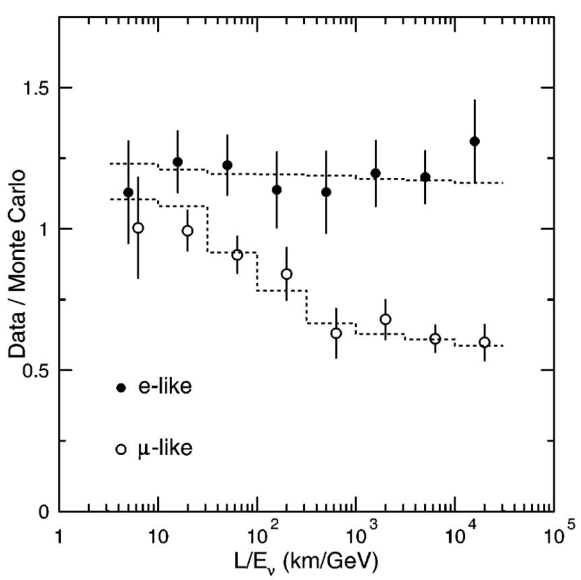
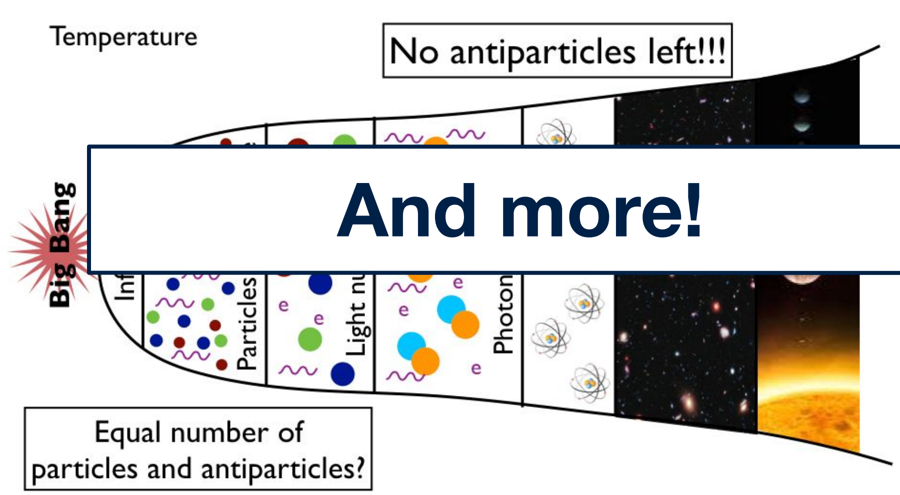
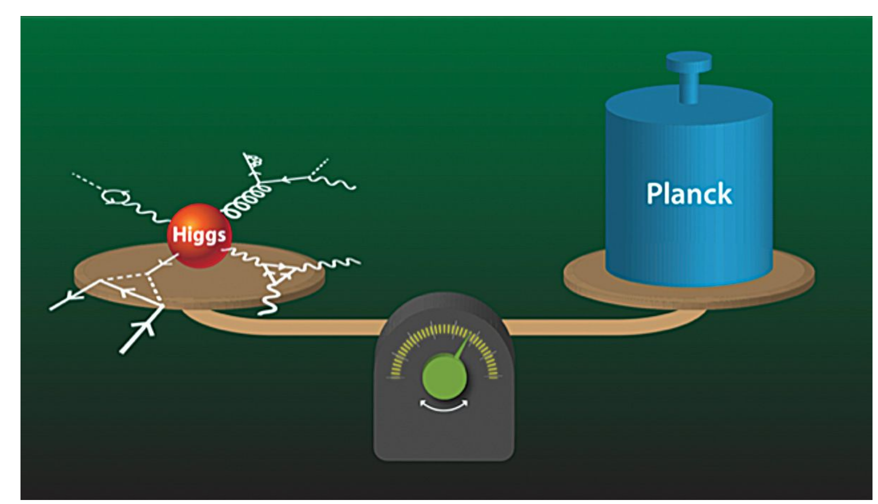






And more!



Dark sector models

Standard model

We are here

portal

e.g. dark photon

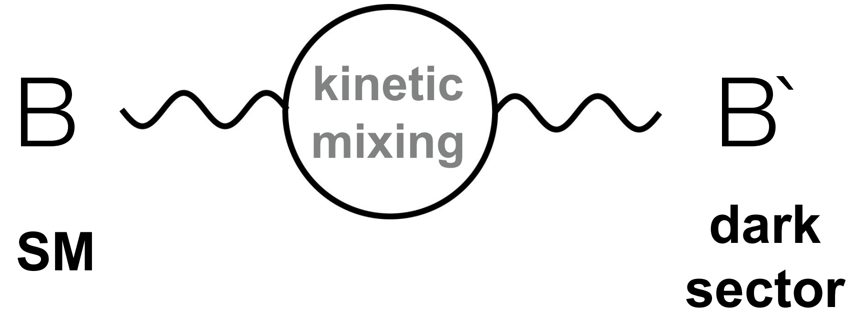
Dark sector

DM is here

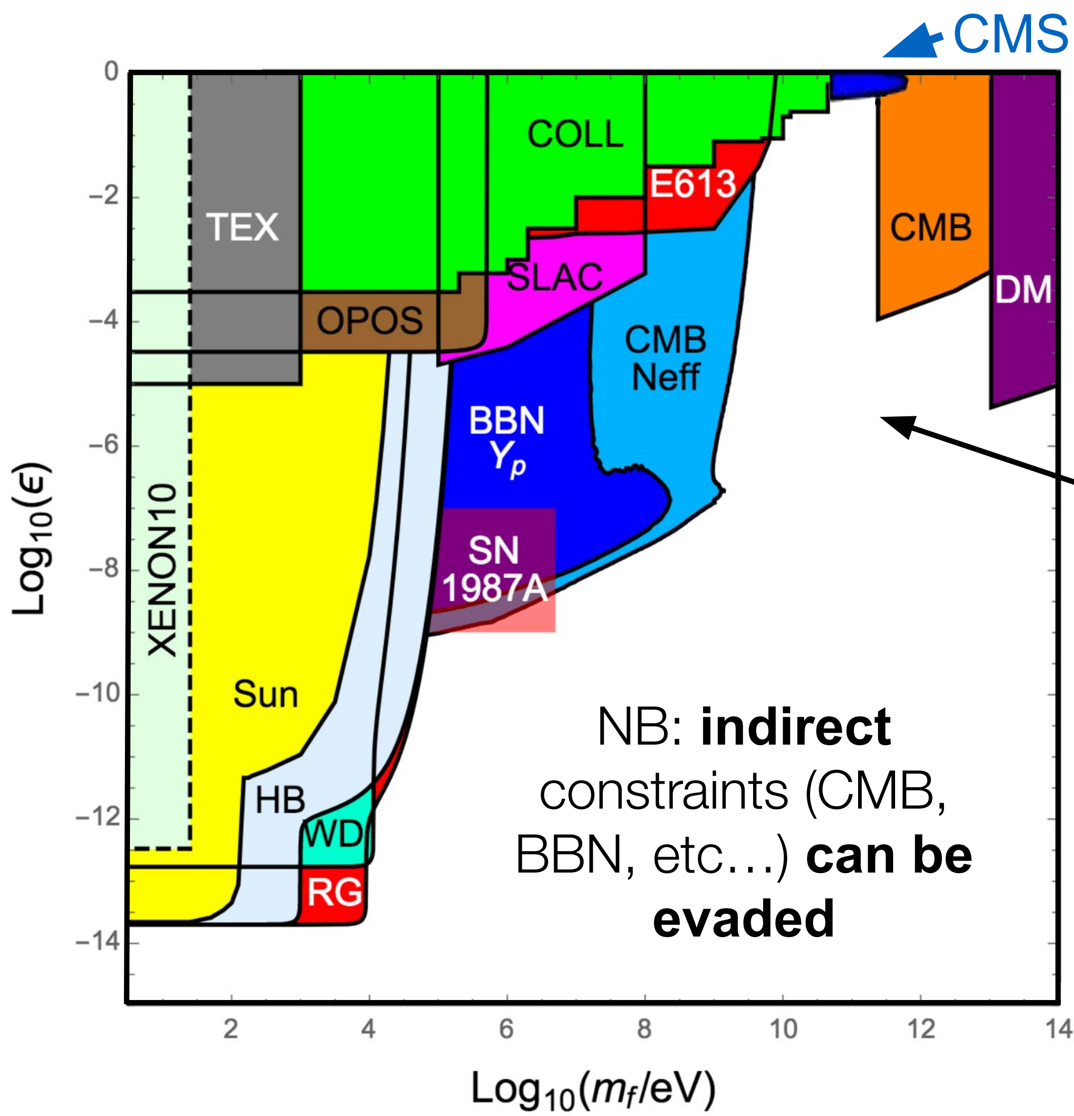
- Dark matter could be part of a **“hidden” universe** with **no SM gauge interactions**
- Hidden universe can have **complex structure** and provide solutions to mysteries beyond DM: neutrino mass, baryogenisis, naturalness,…
- There must be a communication between sectors via a portal

Why MC particles?

Standard model



Dark sector



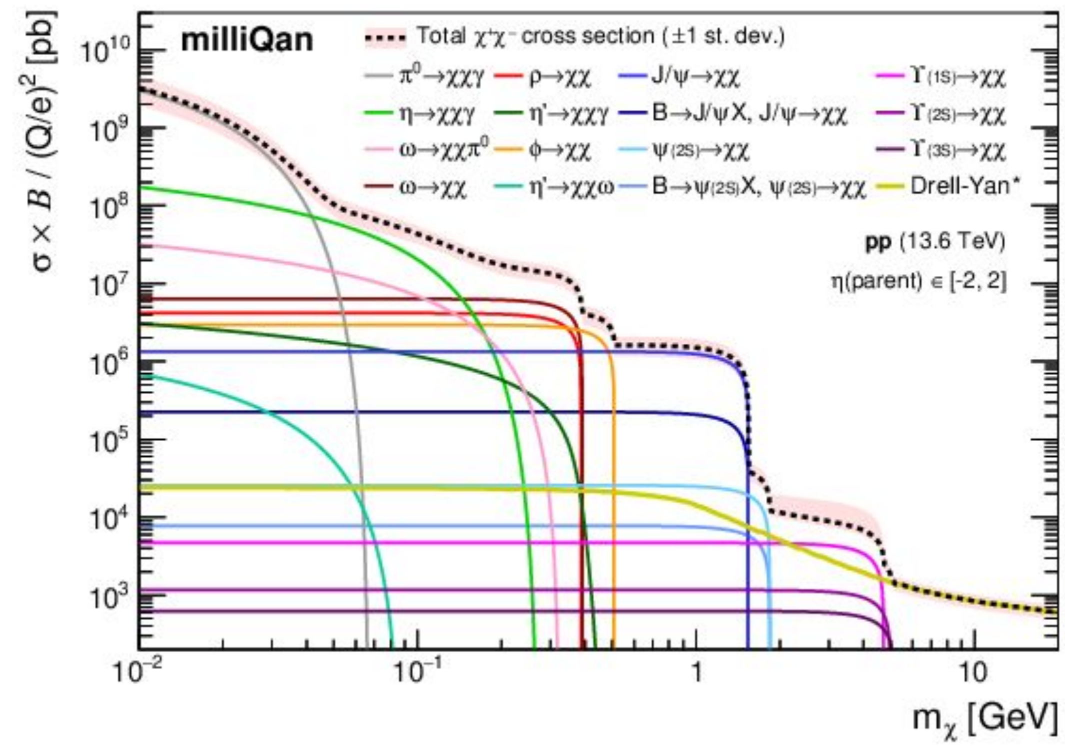
arXiv:1511.01122

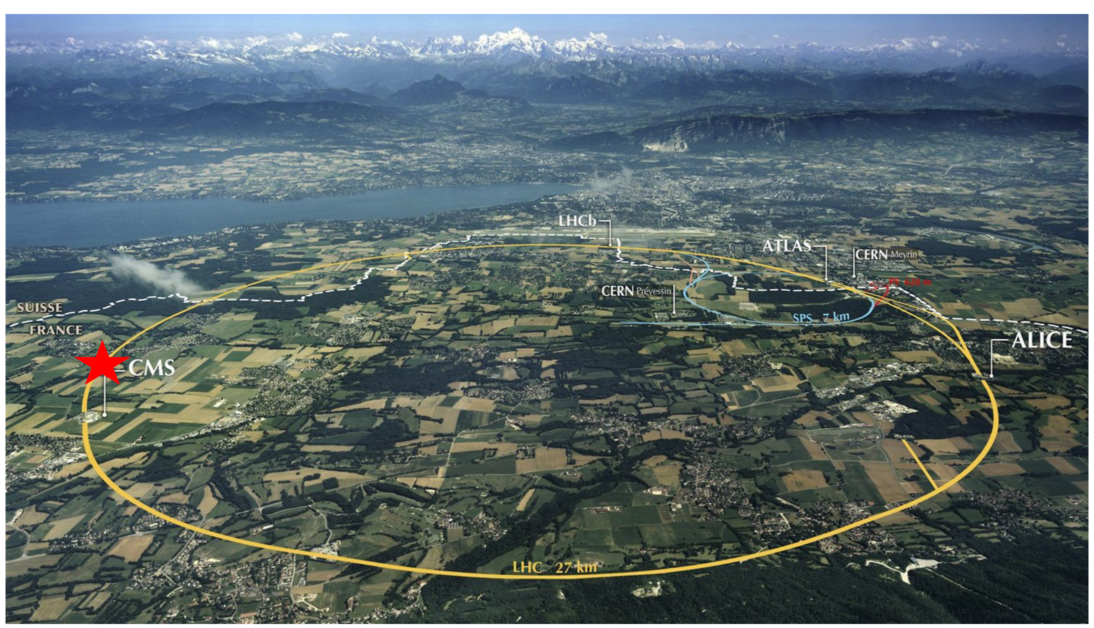
- Millicharged particles (MCPs) arise in **dark sector** theories of DM that include a **massless dark photon**
  - Can also appear in GUTs/string theory
- Past constraints leave big gap in reach for ~ **GeV scale** MCPs
- Could be produced copiously at the LHC but energy depositions too small to see with CMS/ATLAS

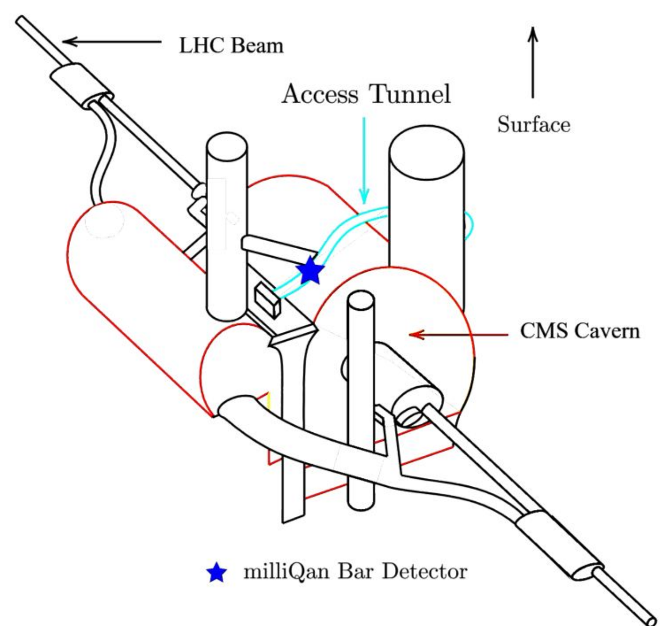
→ target with **dedicated experiments**

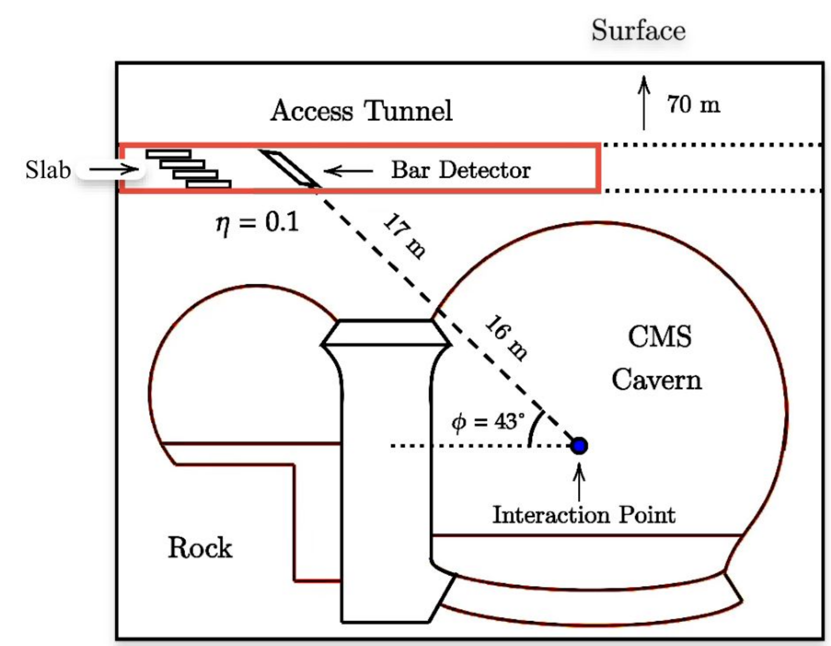
Where?

- MilliQan experiment searches for millicharged particles (mCPs) at the LHC
- It is housed in a gallery just above the CMS experiment
- Shielded from most of the beam backgrounds by 17m of rock and cosmic muons



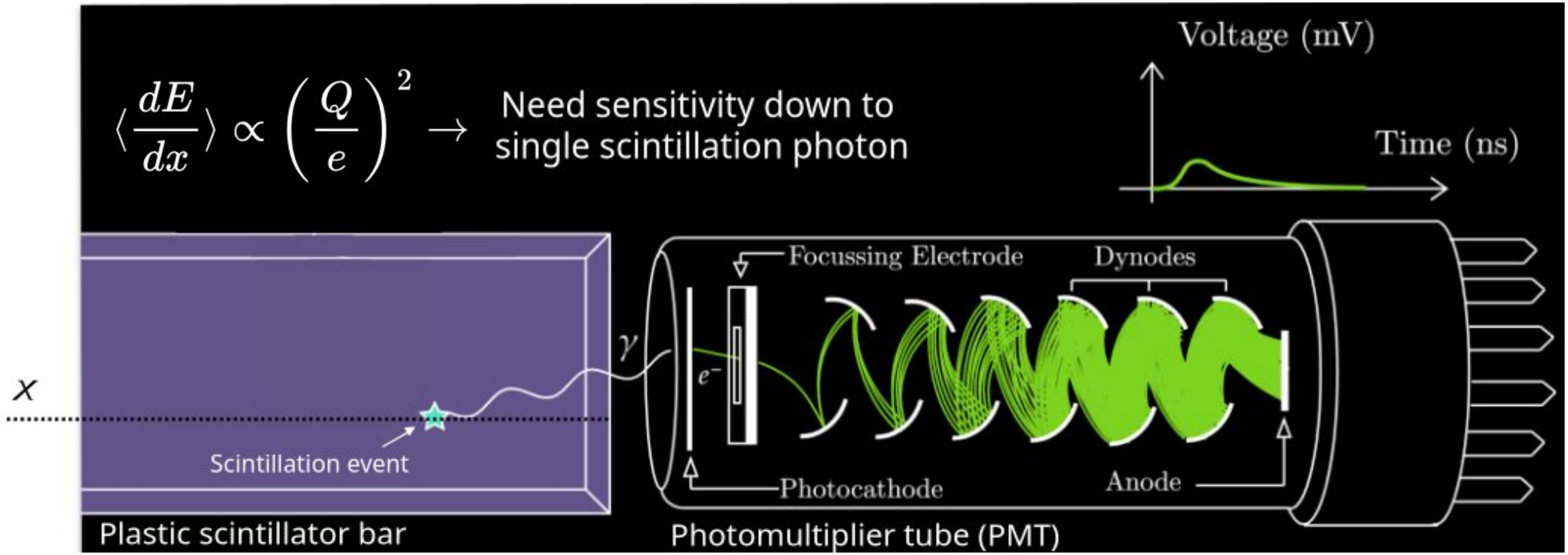






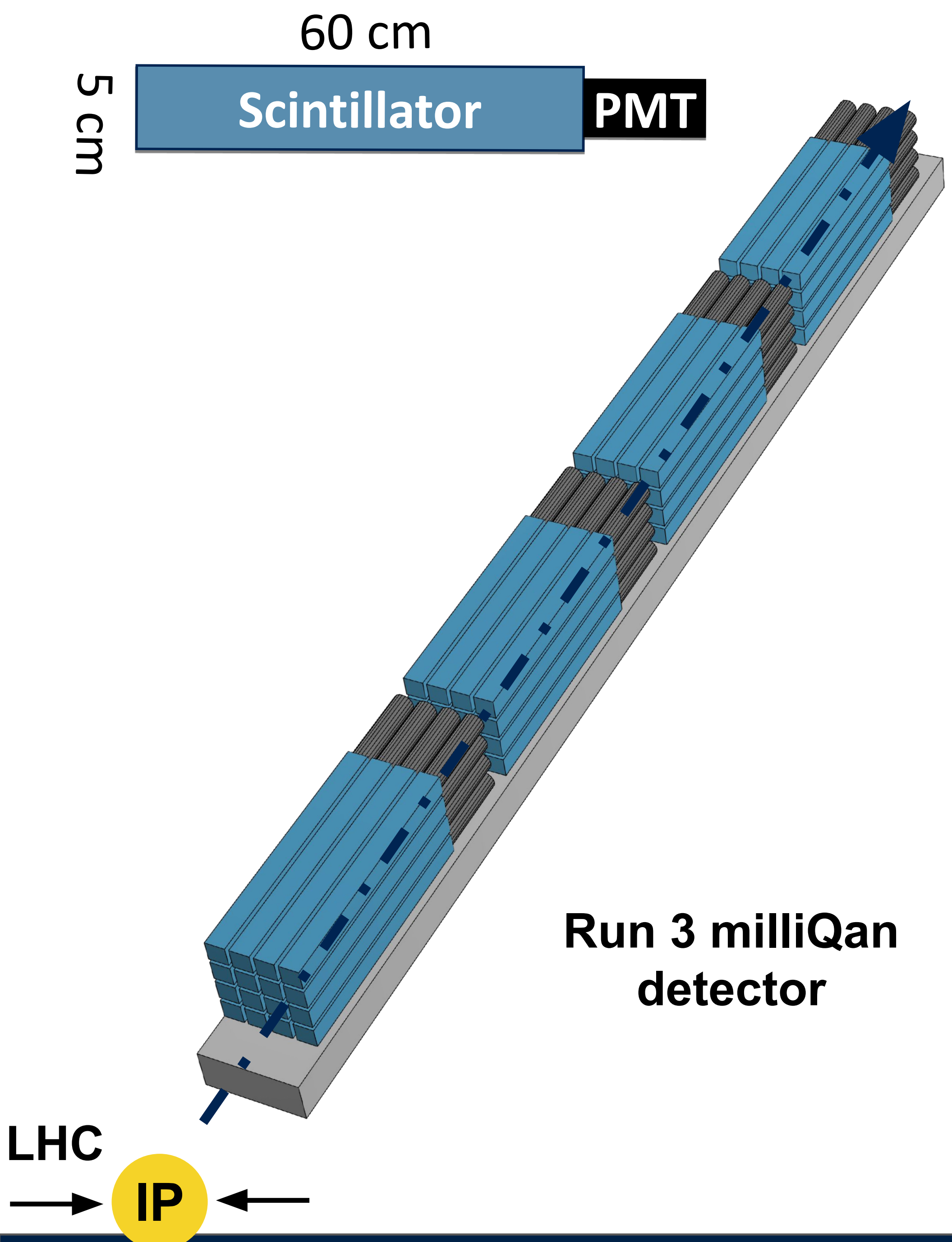
Here!

How?



- The idea for the milliQan experiment is to use scintillators to detect the small ionisation from low charged particles
- Scintillation light is collected by PMTs, providing single photon efficiency
- How to differentiate signal from noise?

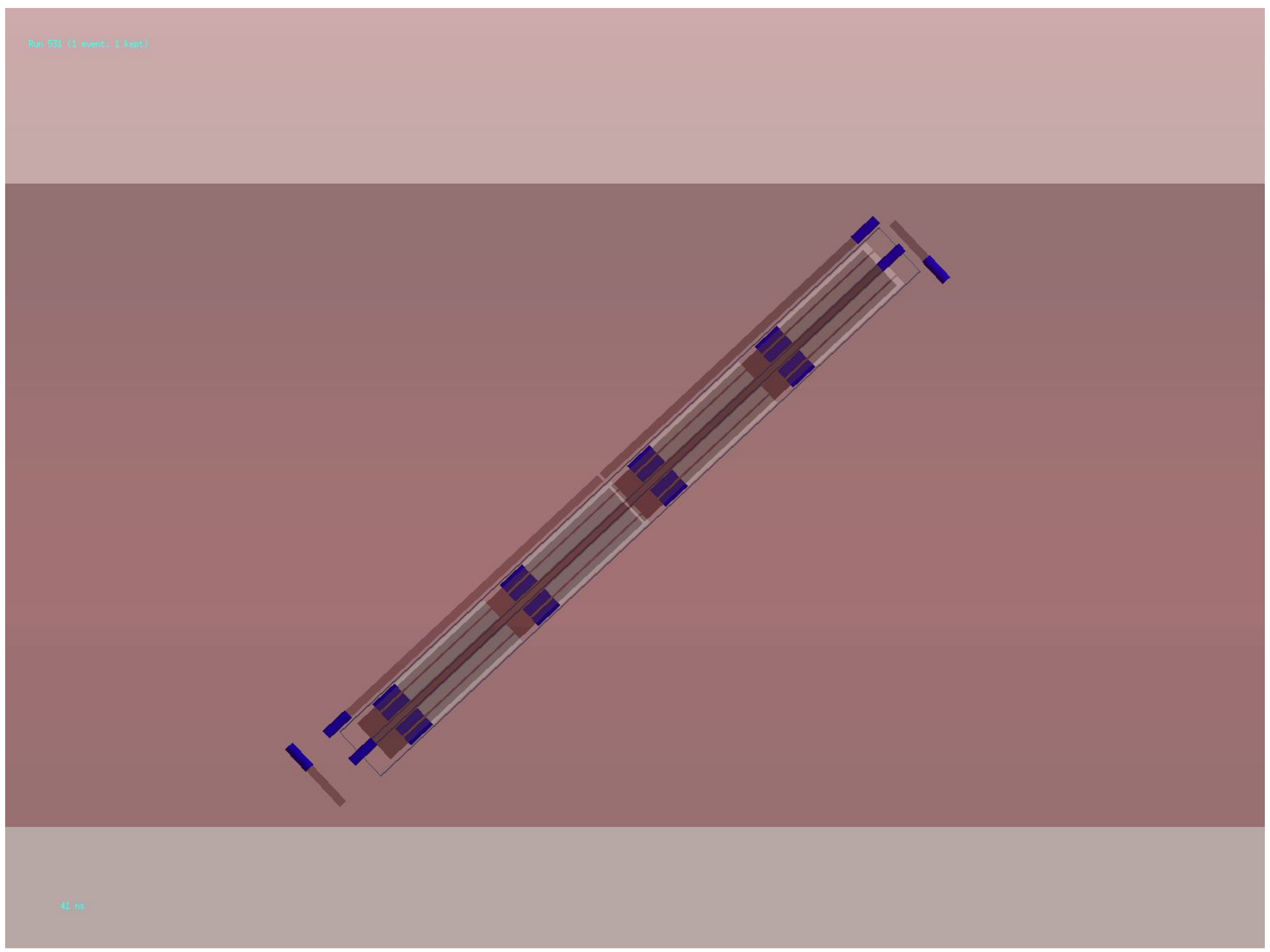
How?



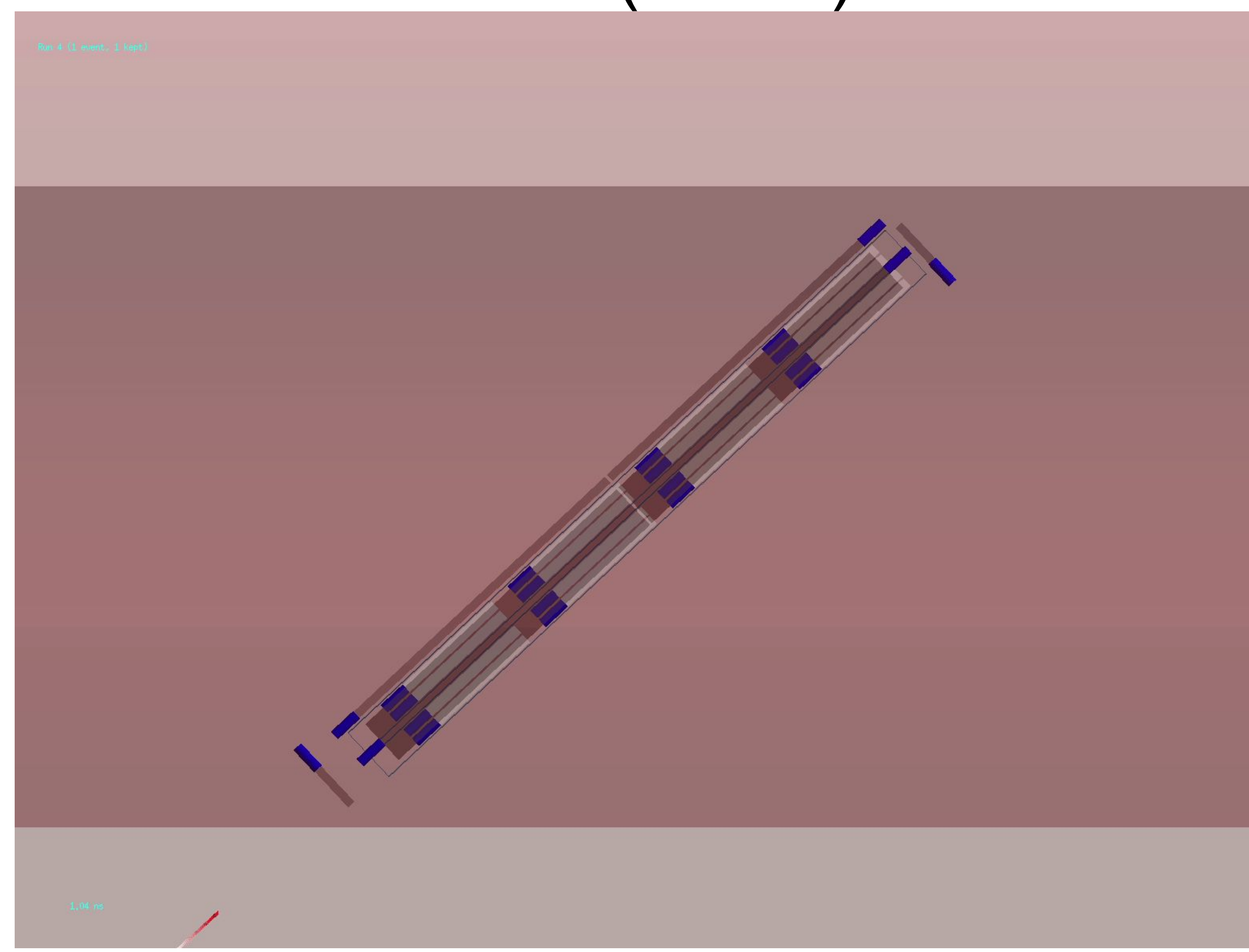
- Use an array of scintillators!
- Expect signal as few scintillation photons in multiple layers
- Control backgrounds: signal in each layer within small (~20 ns) time window and that points towards the IP
- Scalable design, easy to adapt to the available space

The MilliQan detector

Q=0.01e (mCP)



Q=1e (Muon)



Legend: μ, γ, mcp, e⁻, optical photon

MilliQan timeline

milliQan Demonstrator Commissioned

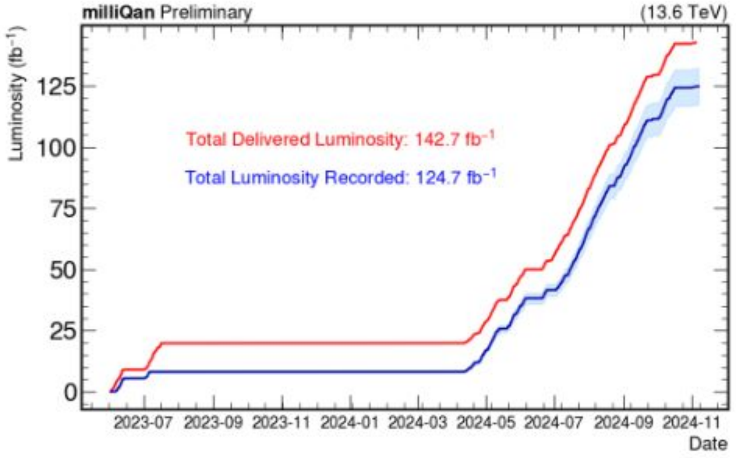
(2018)

[Run 3 projections]

(2021)

Bar Detector Commissioned

(June 2023)



Collected
124.7 fb^{-1} data

(Dec 2024)

[milliQan proposal]

(2014)

[milliQan demonstrator search]

(2020)

Bar Detector Construction Begins

(2022)

Slab Detector Commissioned

(July 2024)

Bar detector search

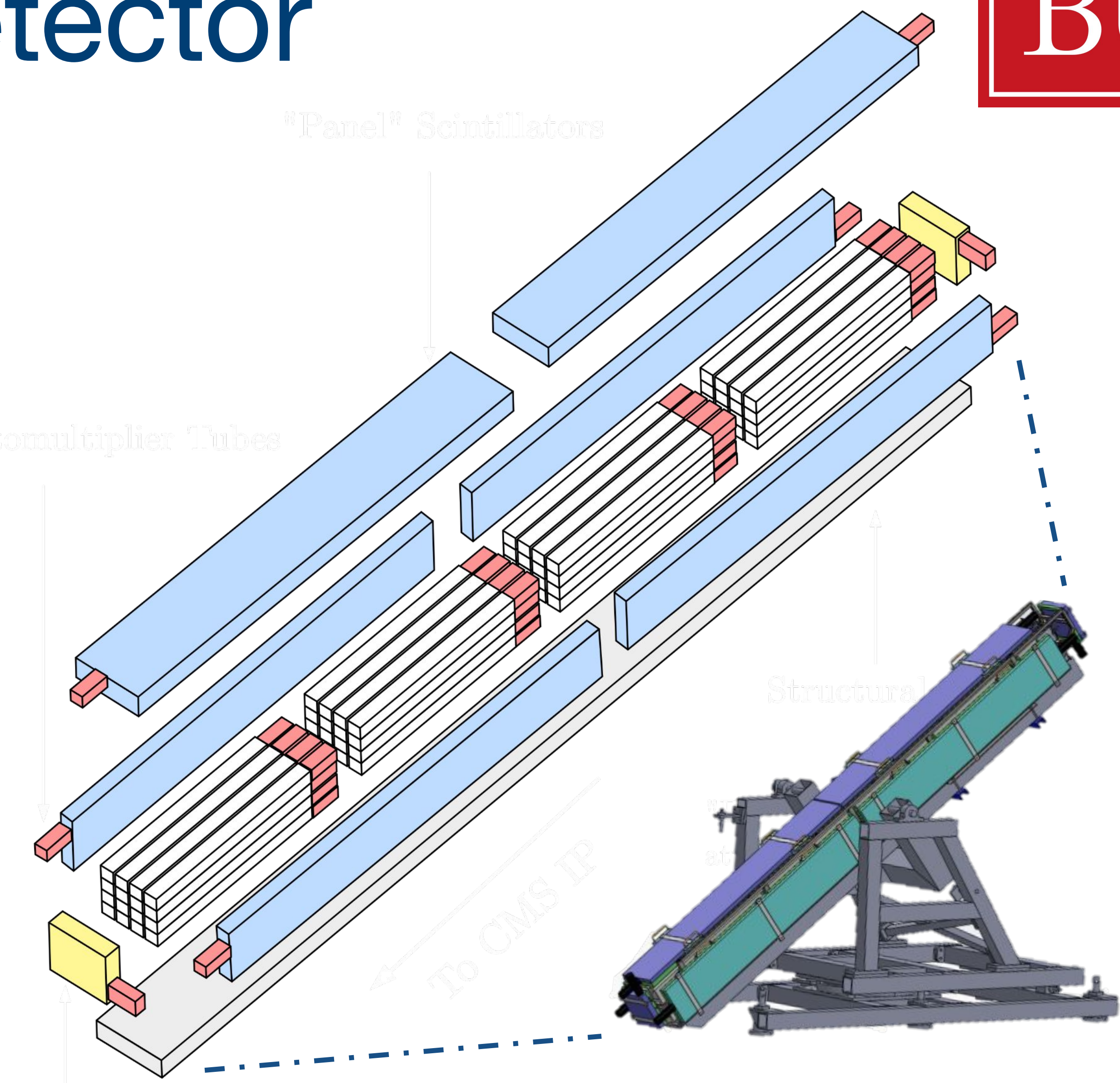
(May 2025)

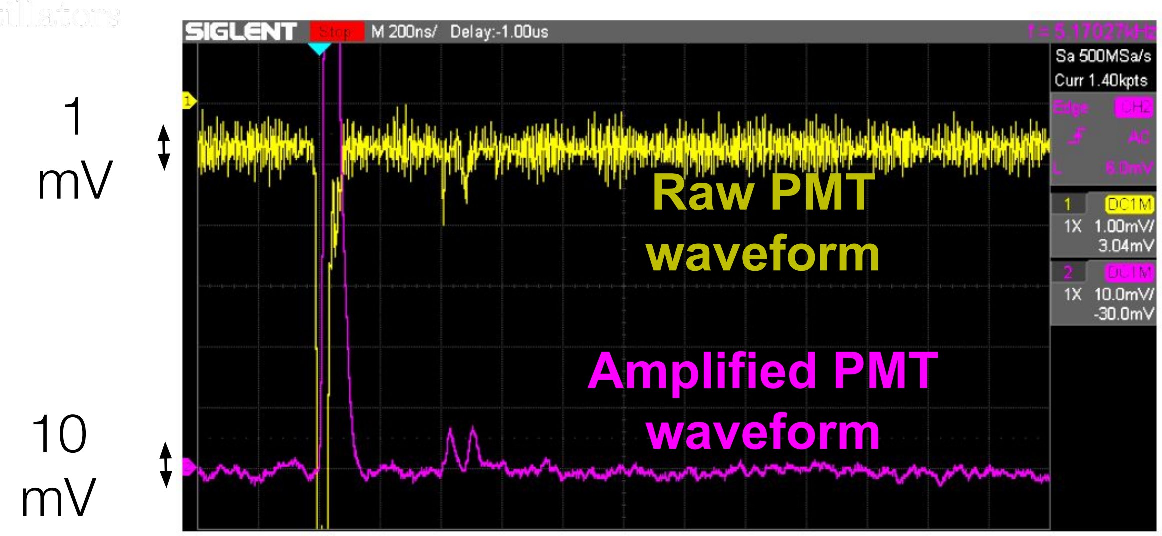
Paper on arxiv in June 2025 ([arXiv:2506.02251] [hep-ex])

Paper published by [PRL] two weeks ago!

Bar detector

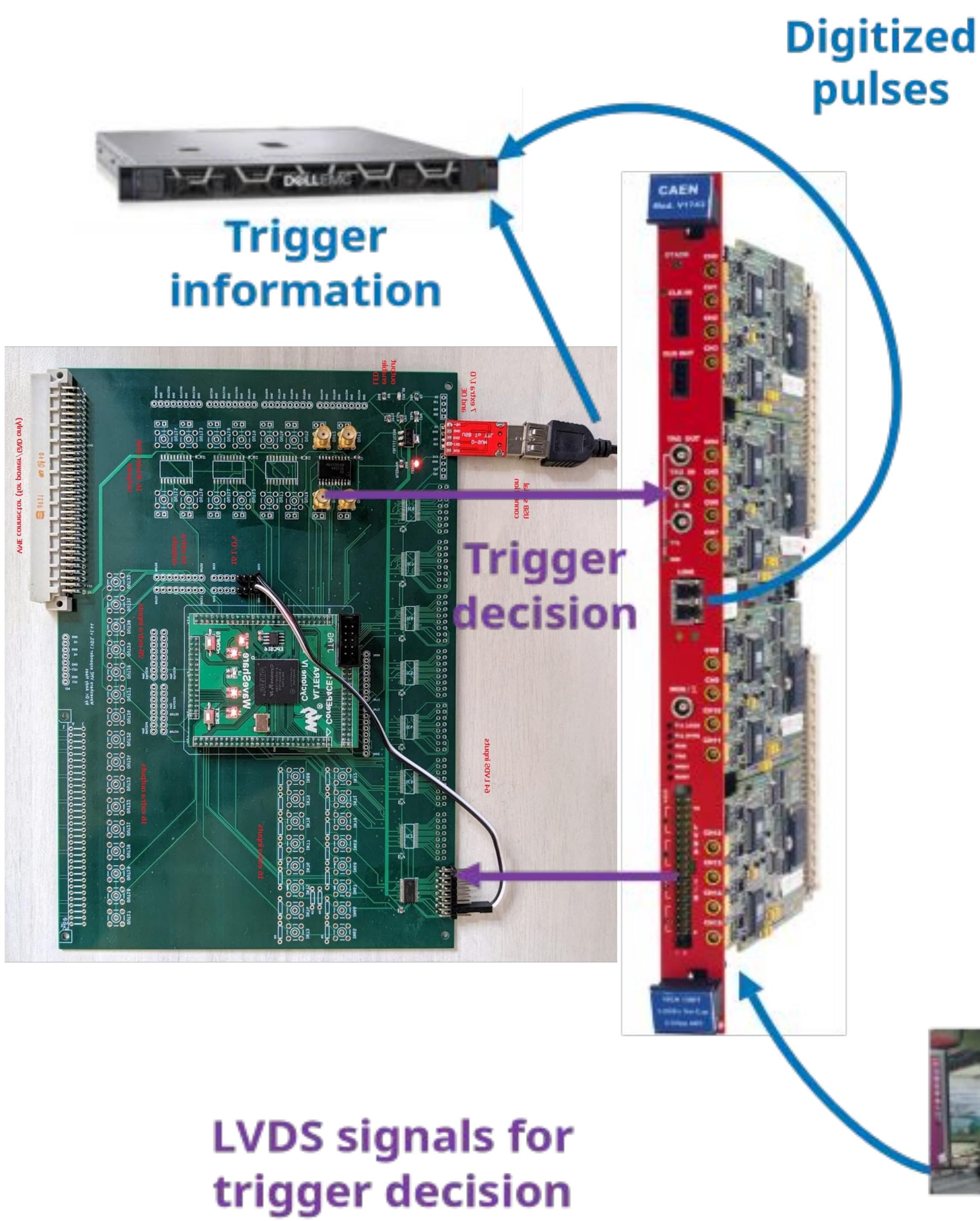
- Array of **four layers** of **4x4 60cm** long **EJ-200 scintillator bars**
- Bars coupled to **R878 PMTs** (amplified to allow SPE sensitivity)
- Veto panels provide **active rejections** of cosmic and beam muon deposits
- DAQ: CAEN V1743 digis coupled to dedicated trigger board

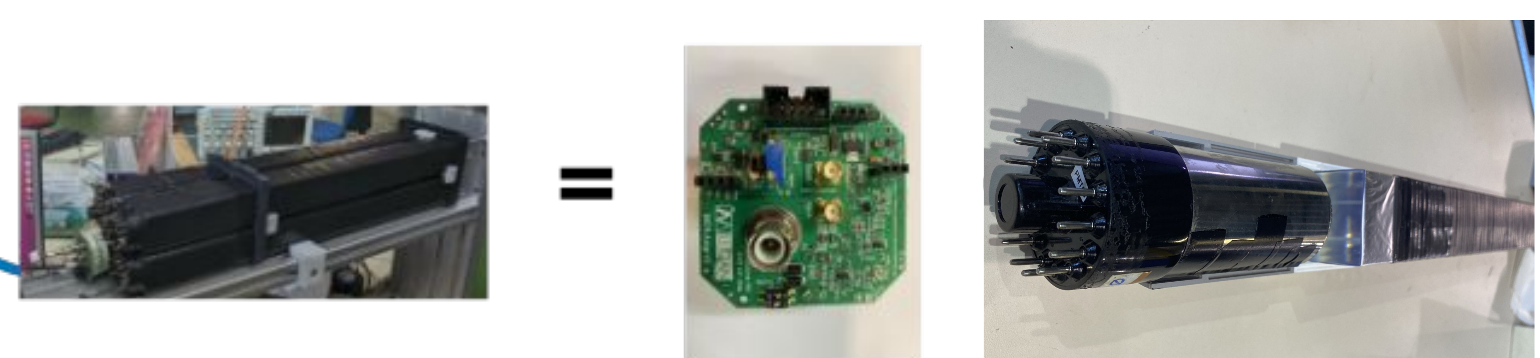




MilliQan DAQ

- High SPE efficiency provided by PMT output amplified with customized base
- Reconstruct complete pulse information using 16 channel CAEN V1743 digitizer with ~GHz sampling frequency over ~ µs readout window
- Five digitizers for the bar detector and six for the slab detector
- Flexible trigger decisions using customized trigger board equipped with Altera Cyclone IV FPGA





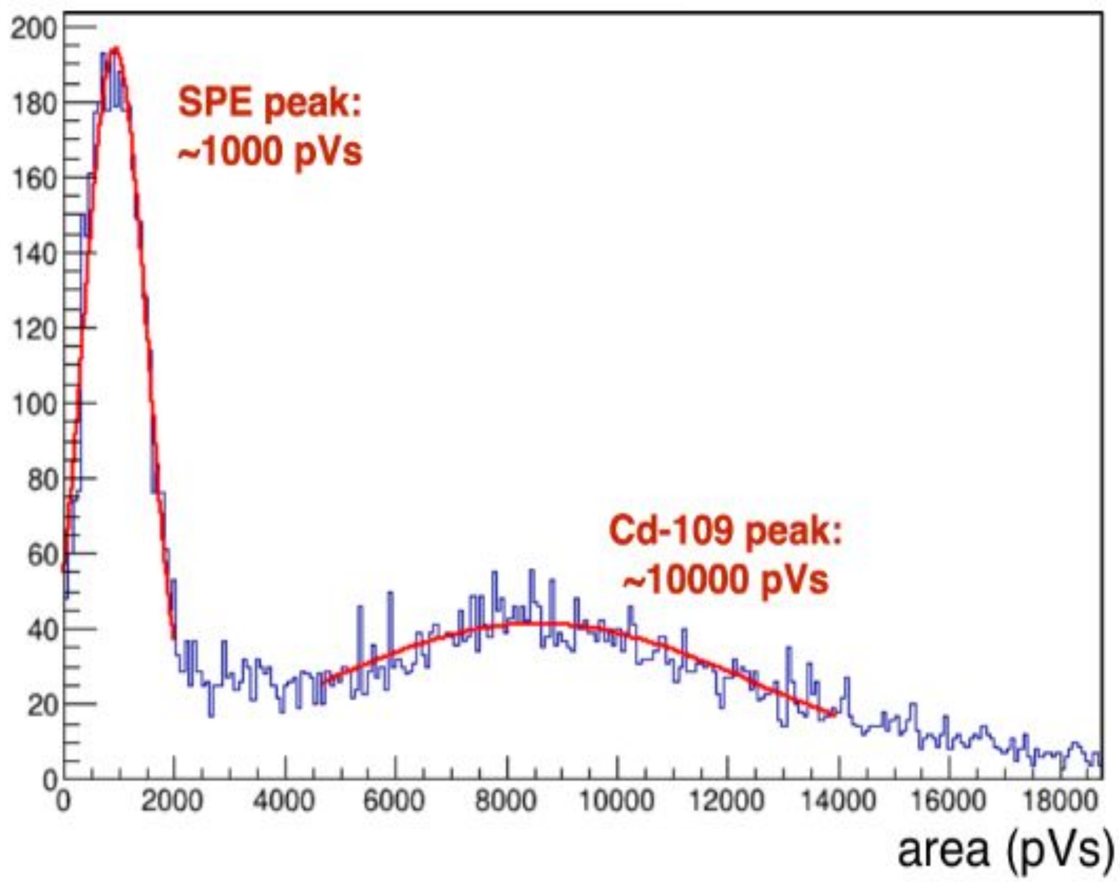
Bar detector construction

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

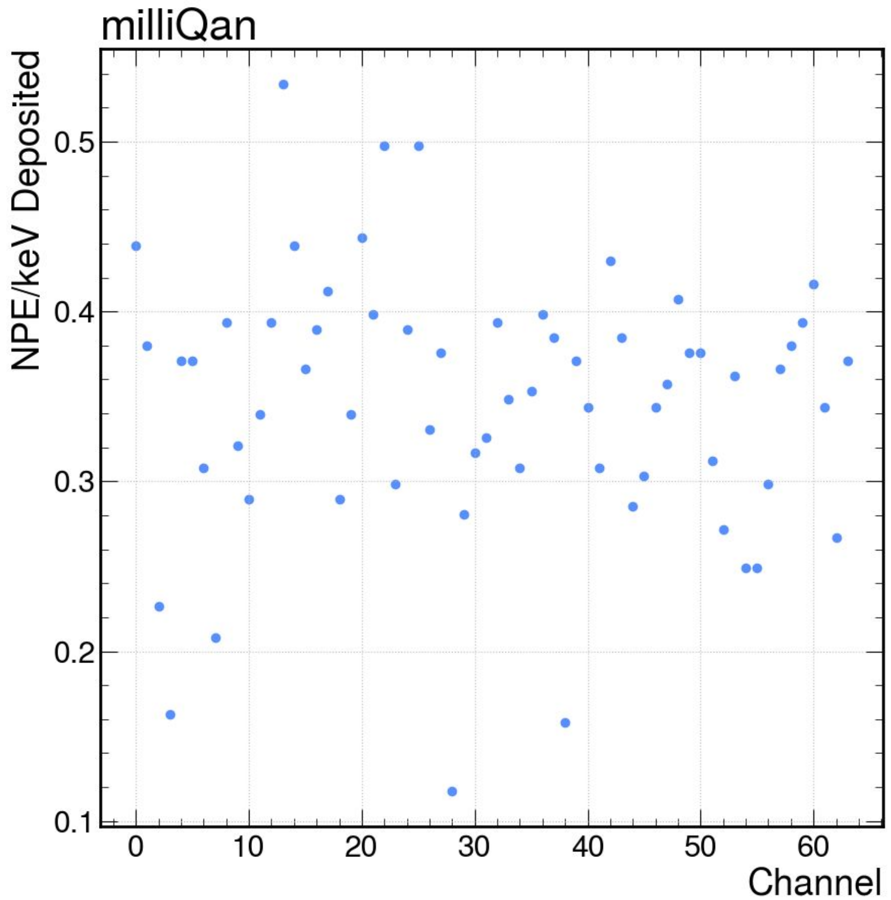
Detector response calibration

- **Cd109 source** (22 keV X-ray) is used in-situ to calibrate detector response to the charge deposition and study individual channel performance
- Response of each of the channels is calibrated and applied to simulation to mimic the detector response

Scintillator and PMTs response calibrated using Cd109 source

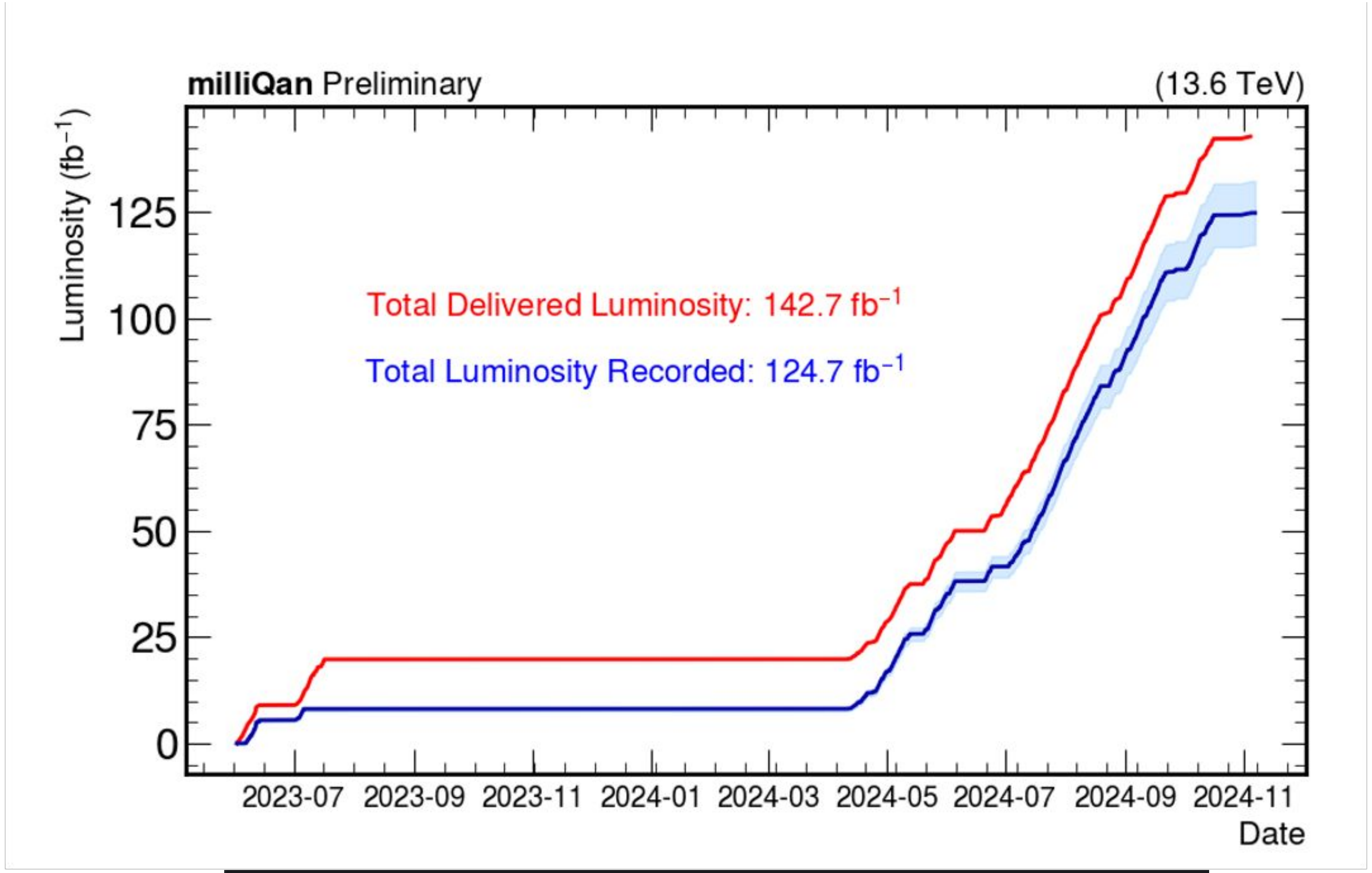


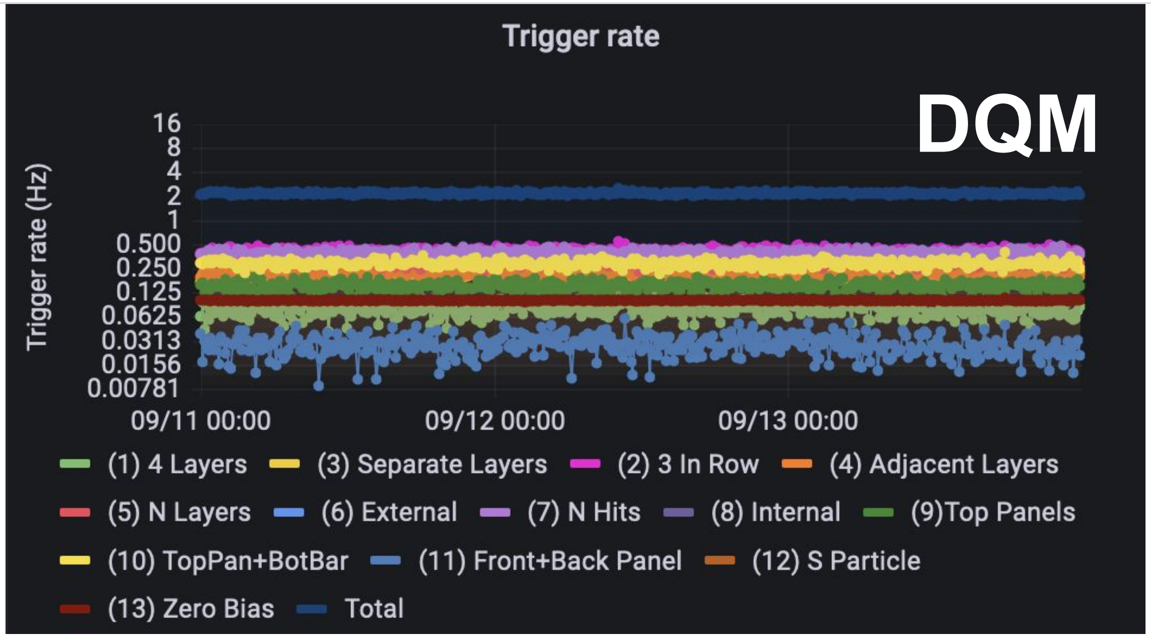
nPE calibrations for each of the channels



Bar detector in Run3

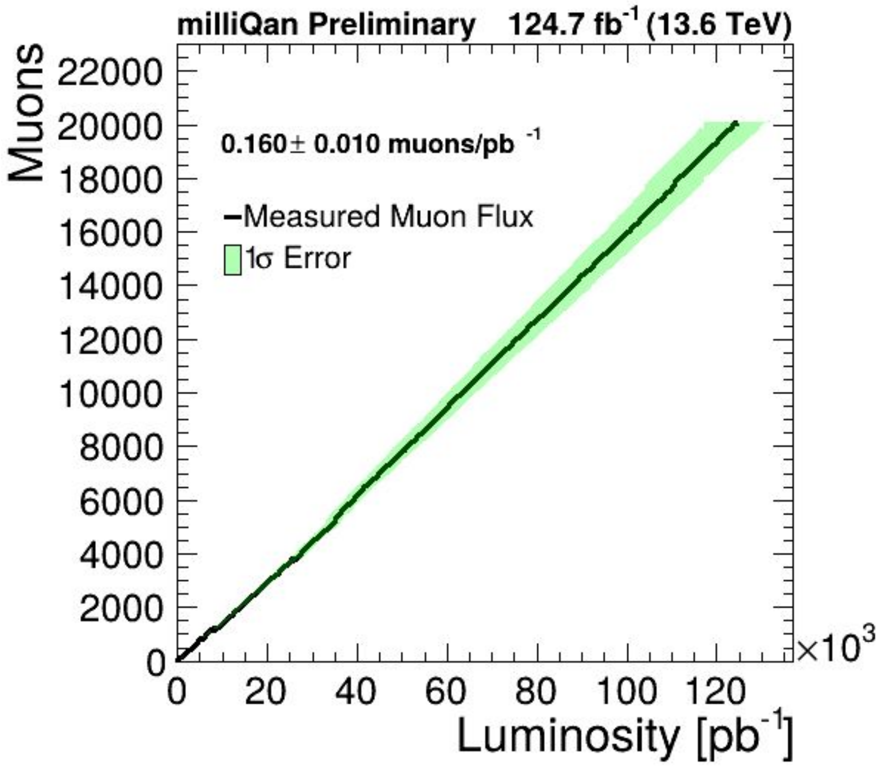
- Detector and GEANT4 simulation **fully calibrated with collected data**
- Collected 124.7/fb of **high quality data** in 7800h of operation
- Web based DQM tools allow rapid response when issues arise → >95% collisional data recorded since 2024!
- Dataset ready to be analysed!



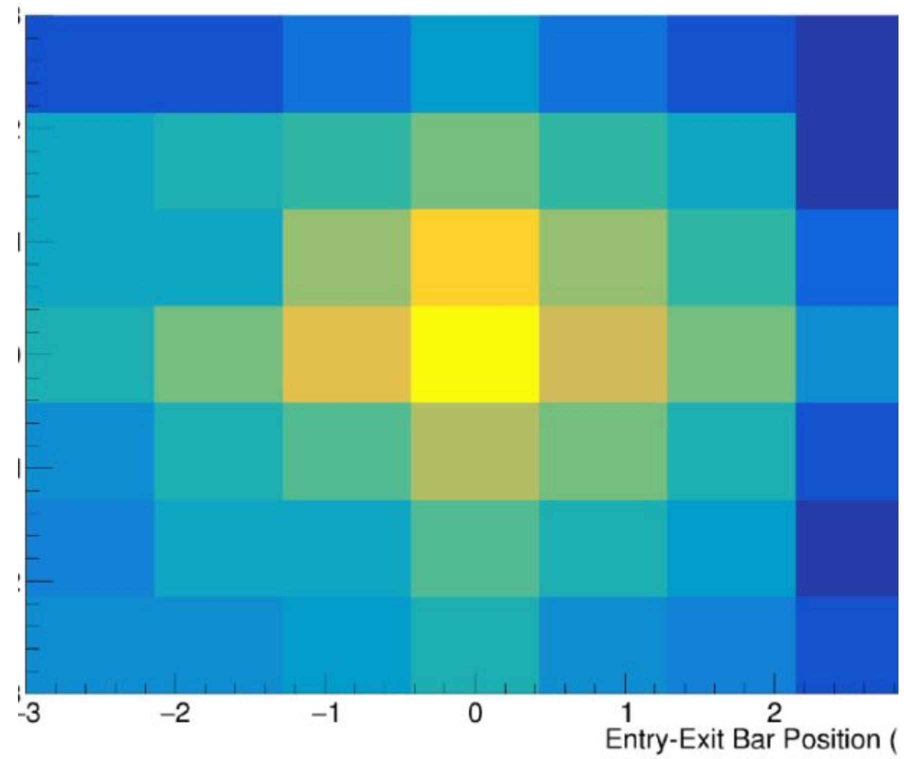


Detector alignment and response

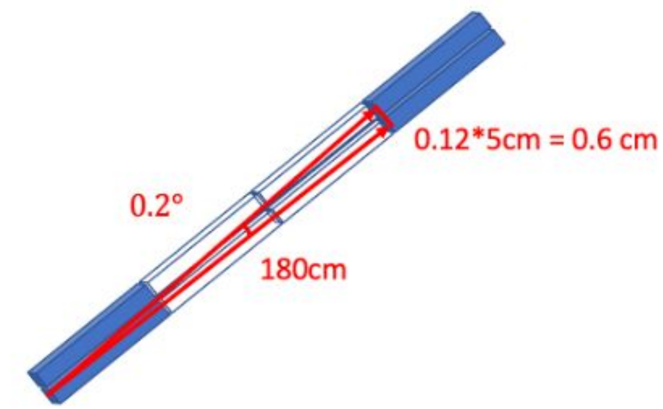
Muon rates



Alignment



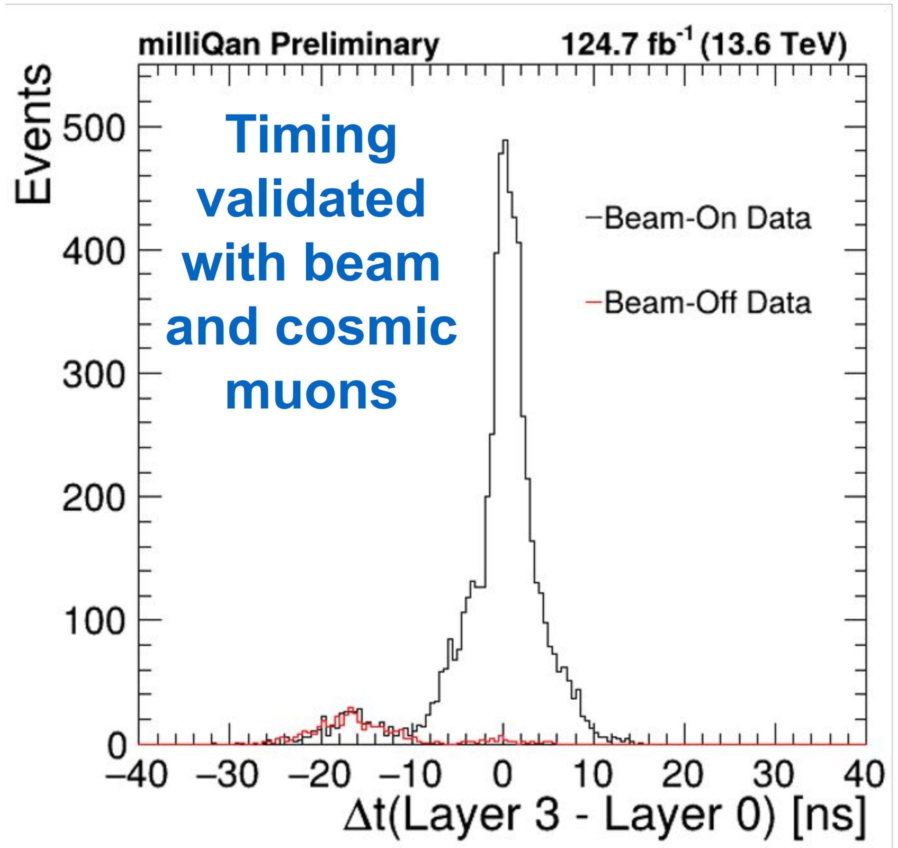
difference → ~0.2° misalignment



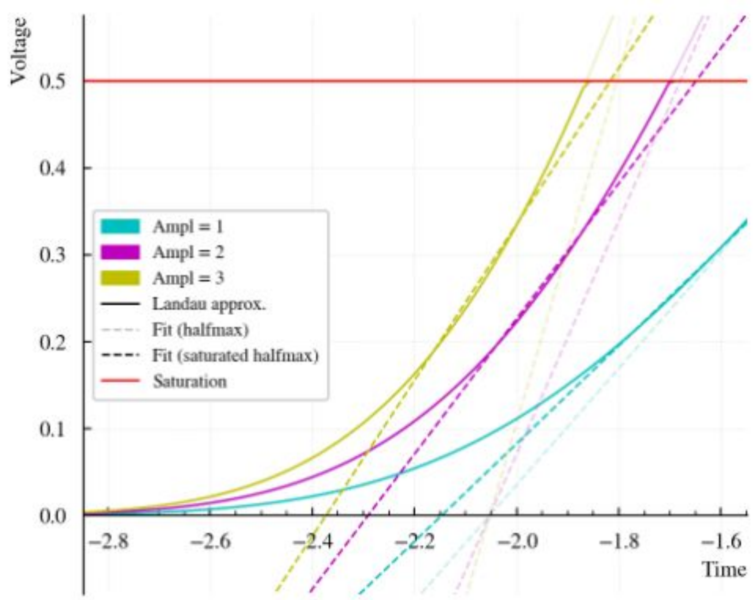
Fixing for 2025 running!

- Muon rate measured to be in **good agreement** with simulation: expect 0.21 ± 0.05 pb^{-1}, observe 0.16 ± 0.01 pb^{-1}
- Using paths of muons measure ~0.2° misalignment → correction applied to MC (~12% impact on signal efficiency)

Timing calibration

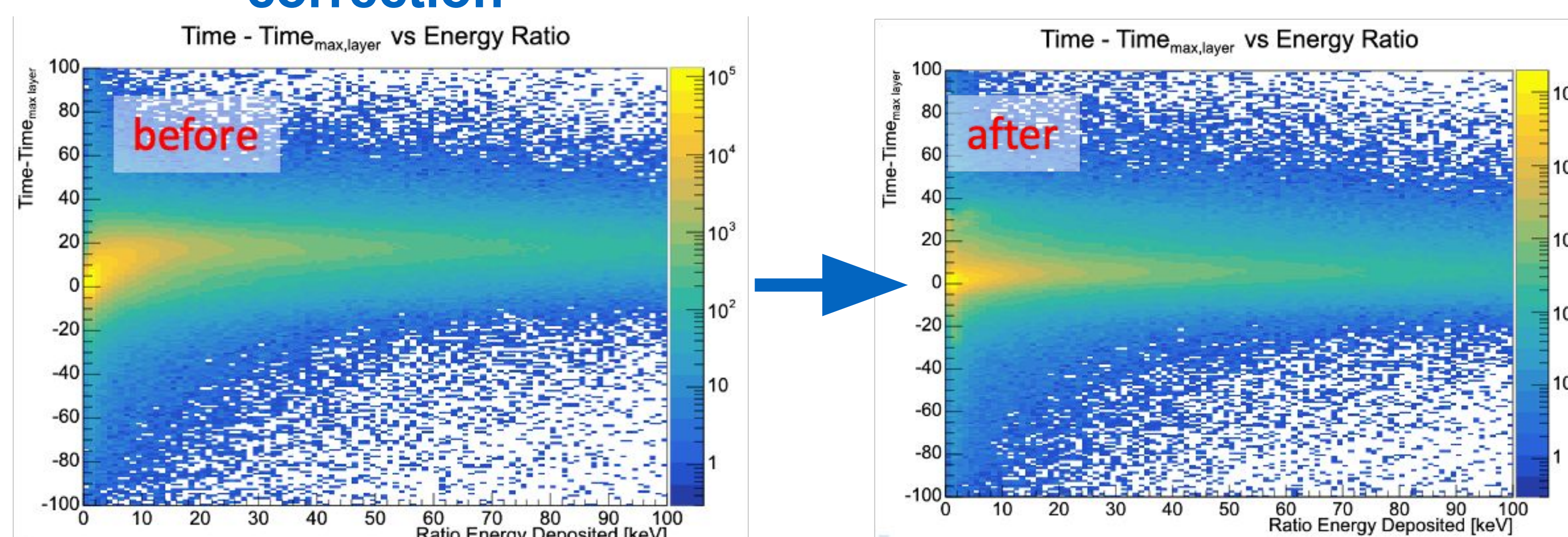


- Differences in electronics/cable lengths cause timing shifts between channels
- Calibrate with beam and cosmic muons such that particles travelling straight through detector from IP have same time in all channels
- Additional “timewalk”correction applied to ensure constant timing vs pulse area



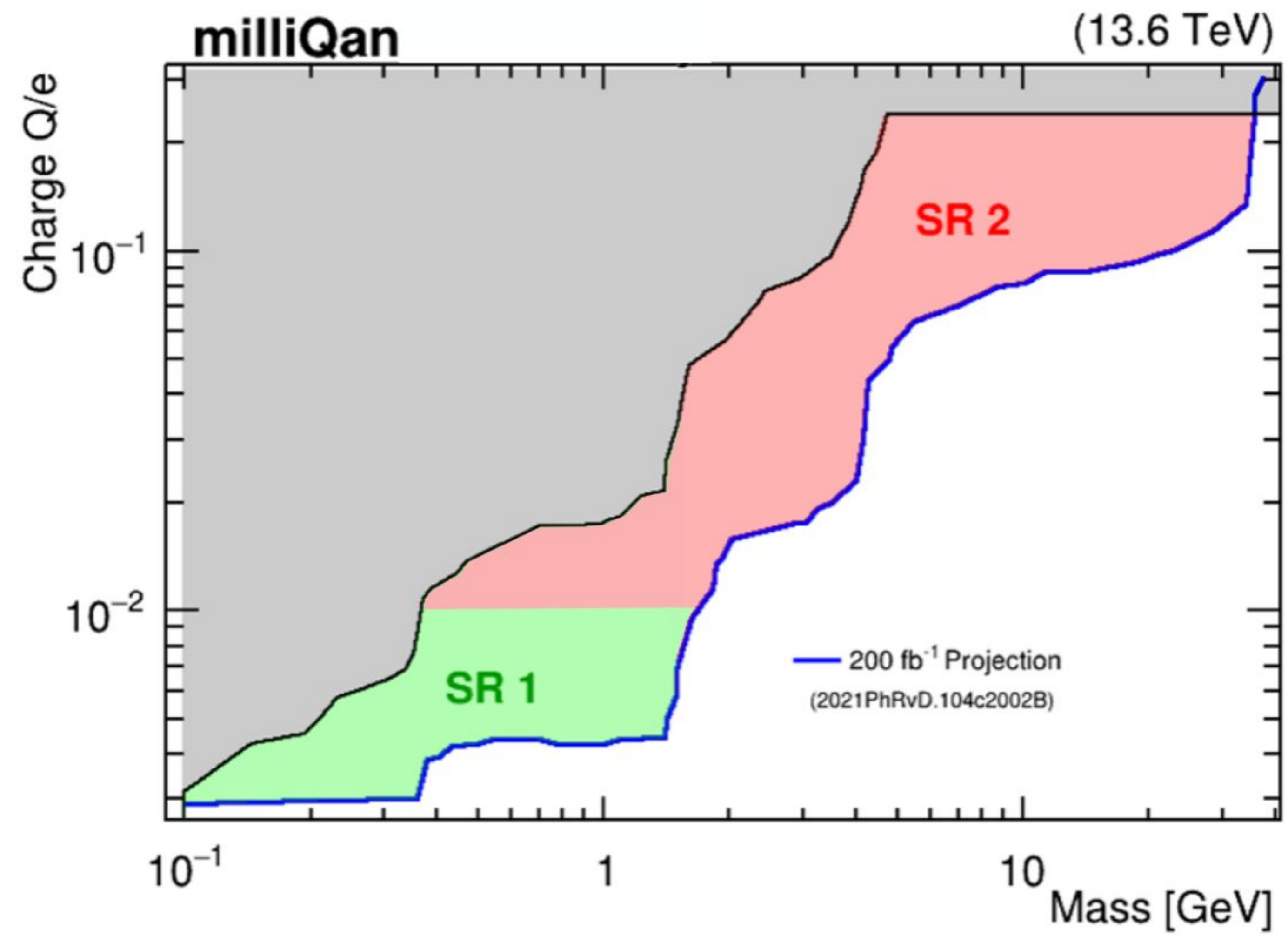
Area of pulse impacts associated time

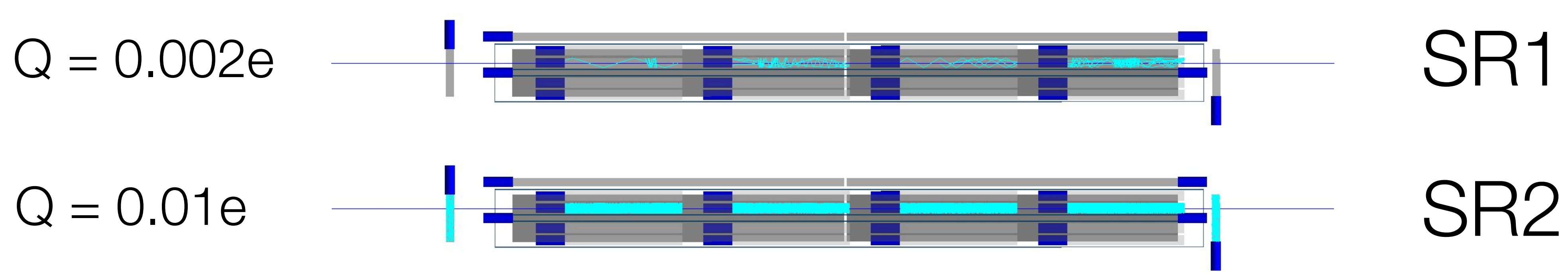
Timewalk correction



Signal categorizations

- After selections categorize into two orthogonal signal regions
- SR1: lower charges
  - Veto hits in **front/back panels** and **>1000 keV** deposited in any bar
- SR2: higher charges
  - Require **≥1 front panel hit** (<50 nPE)





Background prediction/validation: SR1

- 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 of one bar/layer)

Beam-off SR1

Prediction: 0.32 +0.24/-0.16
Observation:0

Beam-on SR1 control region

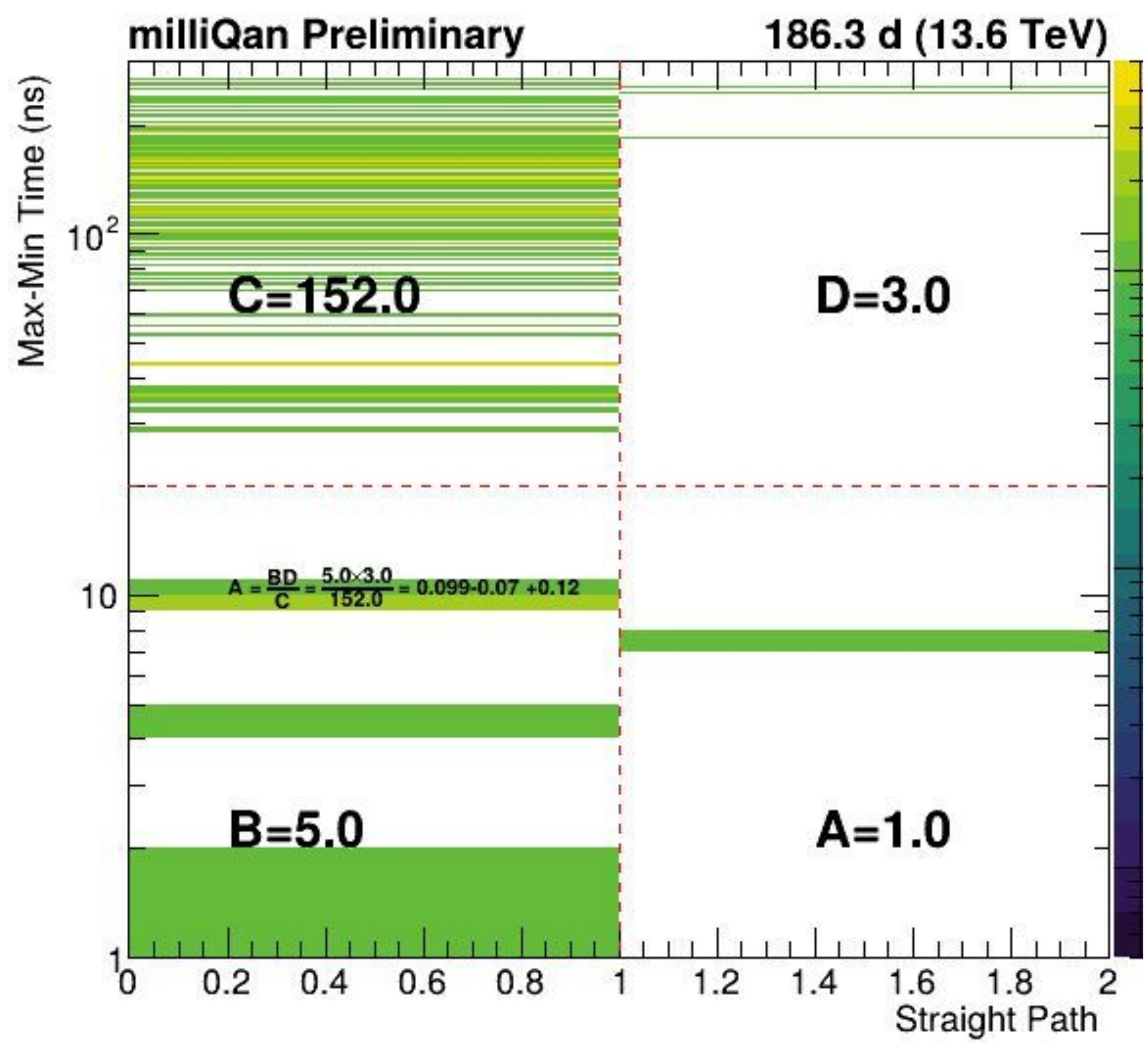
Prediction: 0.31 +0.28/-0.18
Observation: 0

SR1 unblinding

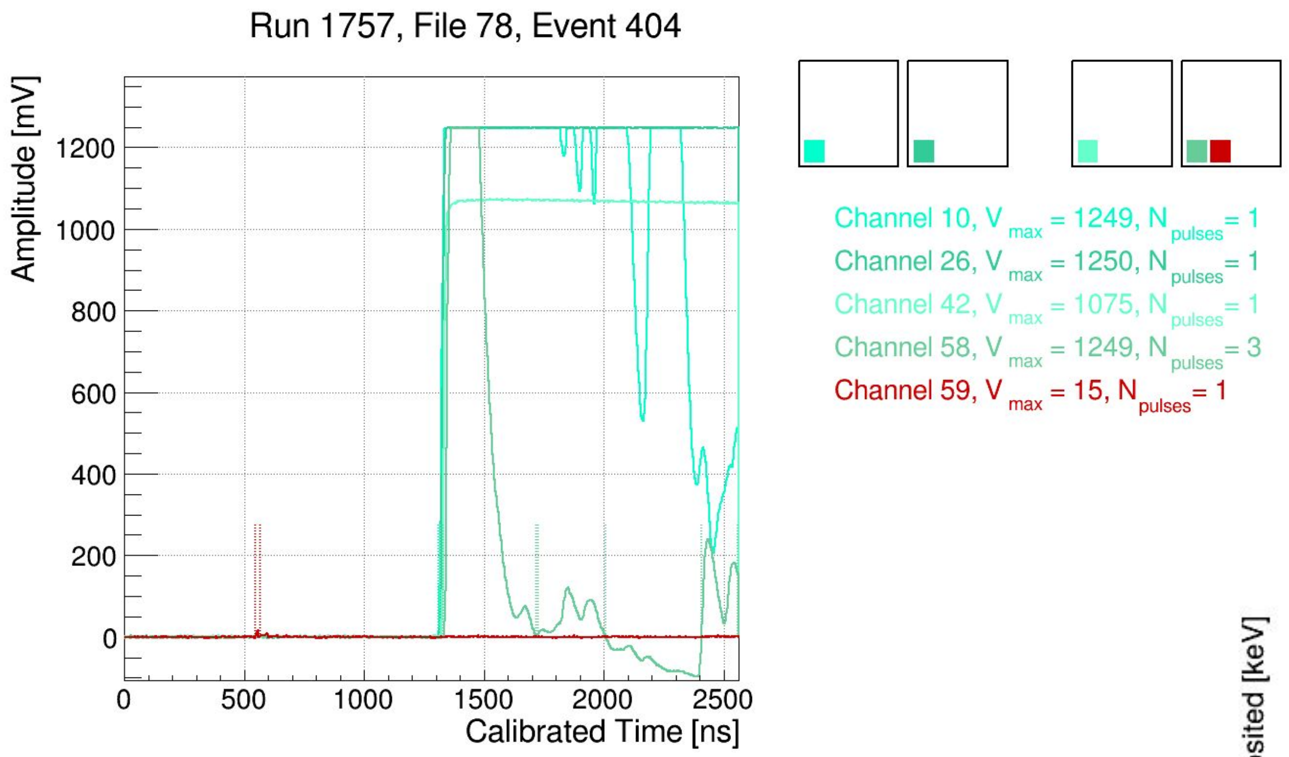
- Prediction: 0.1 +0.12/-0.07
- Observation: 1

Result: agreement within ~1.6σ

Mildly interesting?



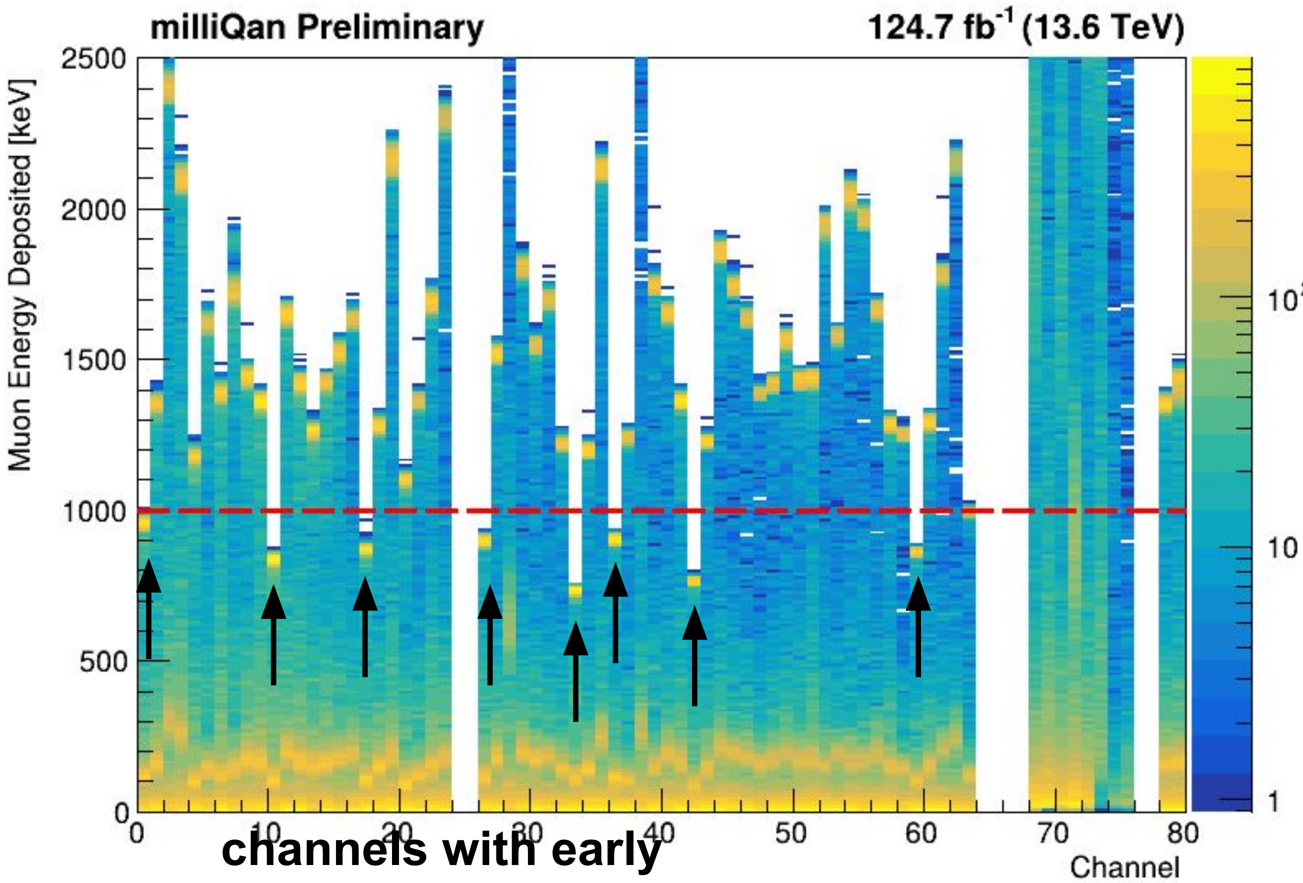
Muon veto fix



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

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

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



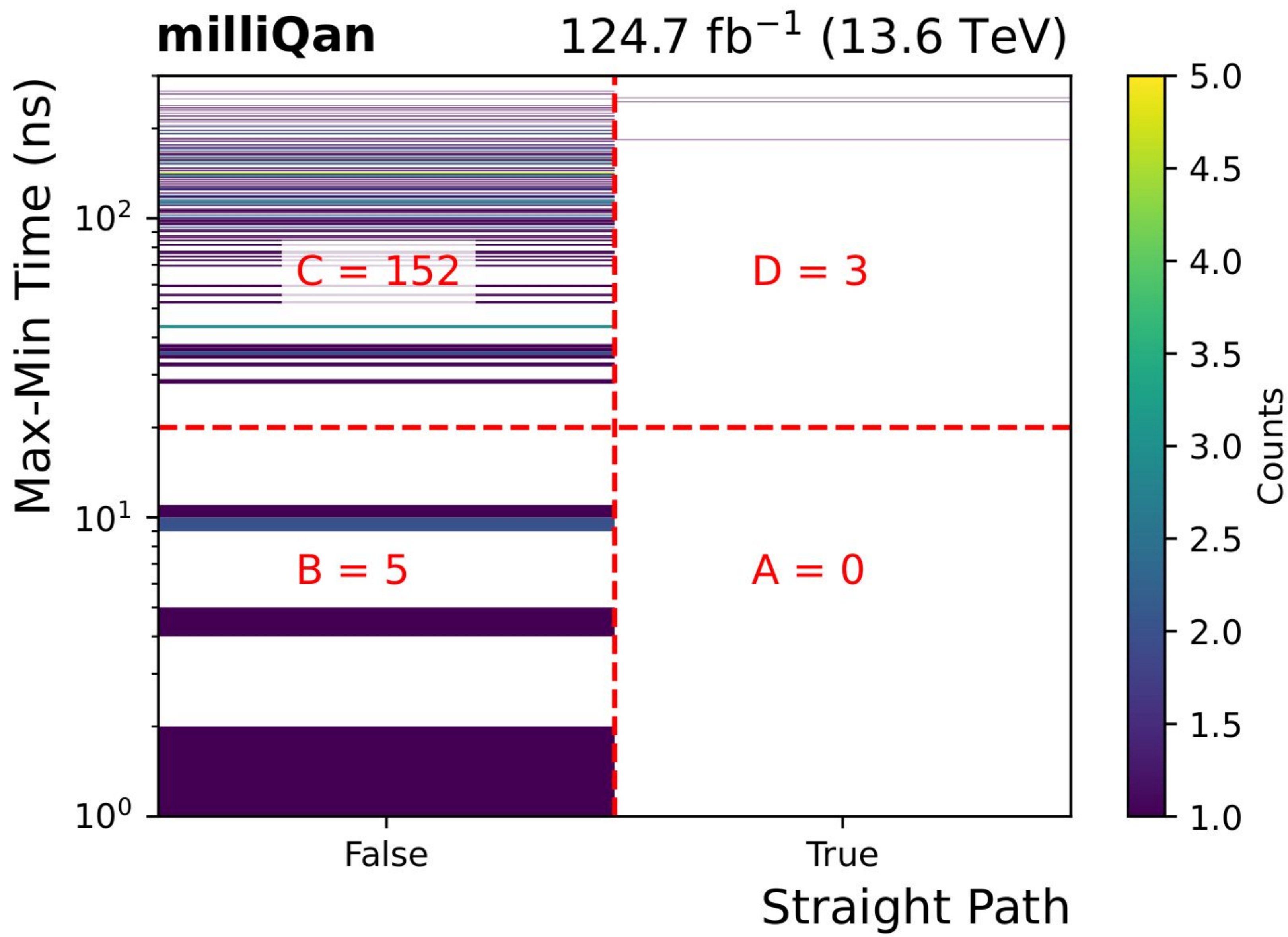
channels with early saturation

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

SR1 (re)unblinding

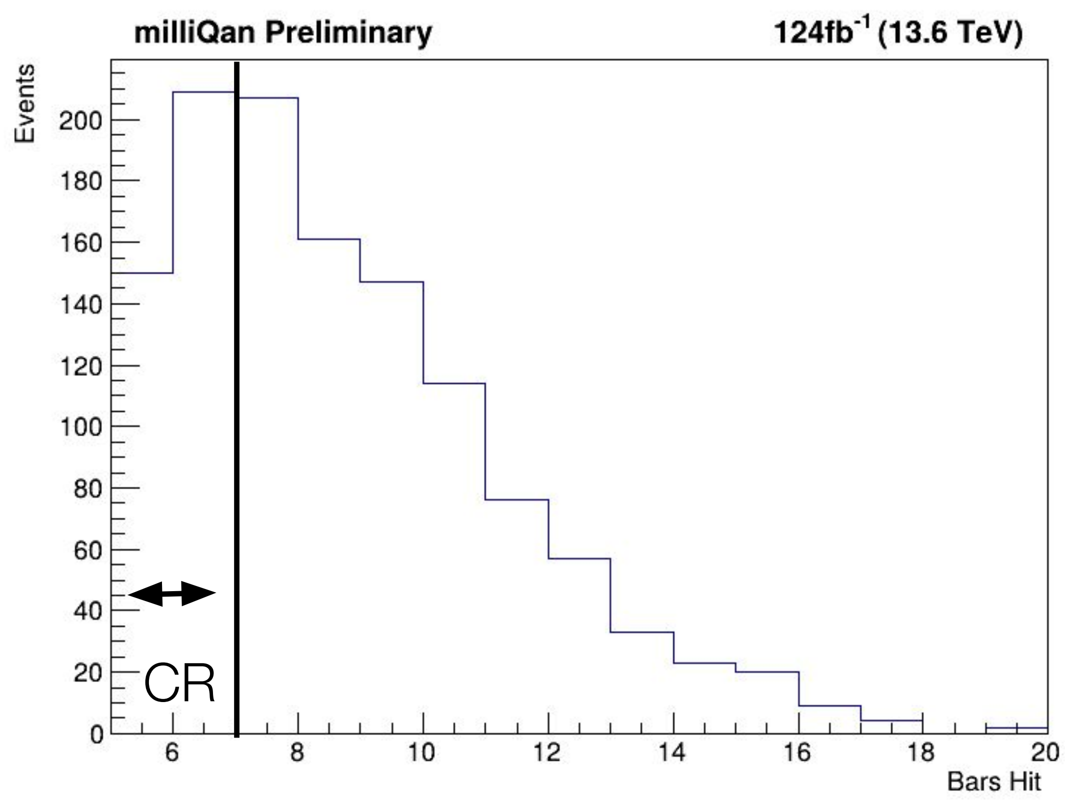
- Prediction: 0.1 +0.12/-0.07
- Observation: 0

Result: no signal
:(



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 panel nPE** and **number of bar** requirements
- Validate prediction method using 5-6 bar **control region**



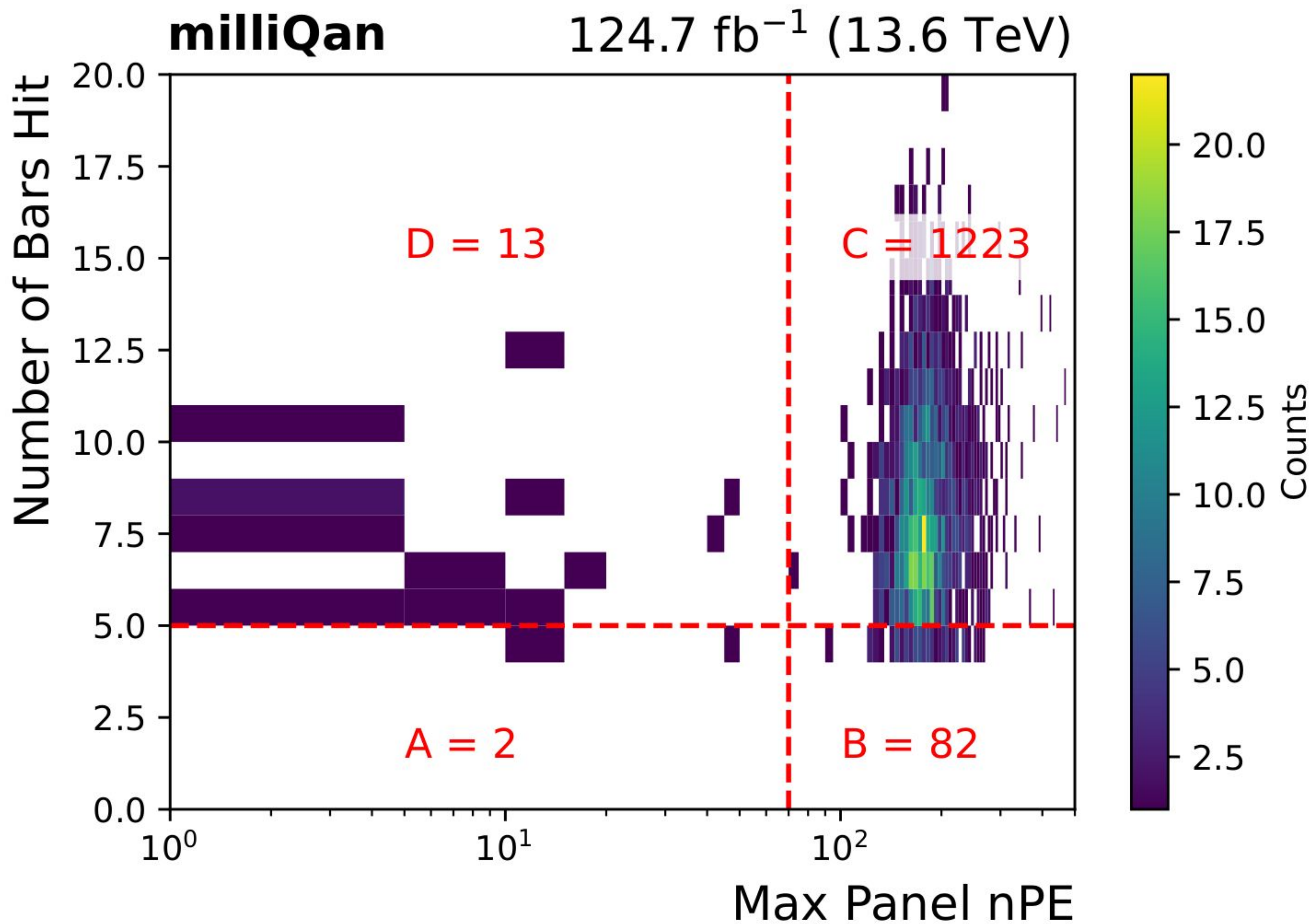
Beam-on SR2 control region

Prediction: 3.4 +1.69/-1.20
Observation: 5

SR2 unblinding

- Prediction: 0.87+0.33/-0.26

- Observed: 2

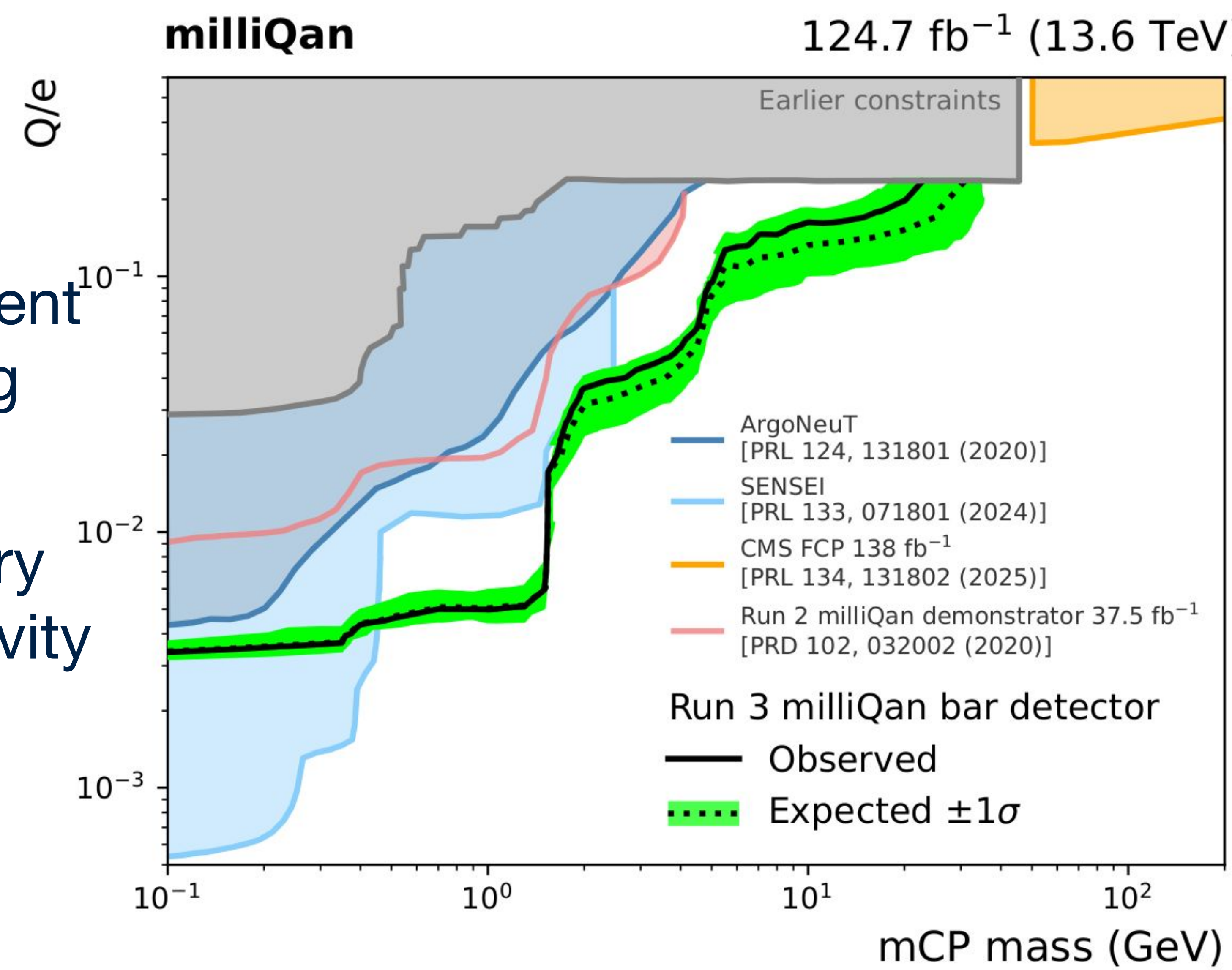


Result: agreement within ~1.2σ

No significant excess! Proceed to set limits

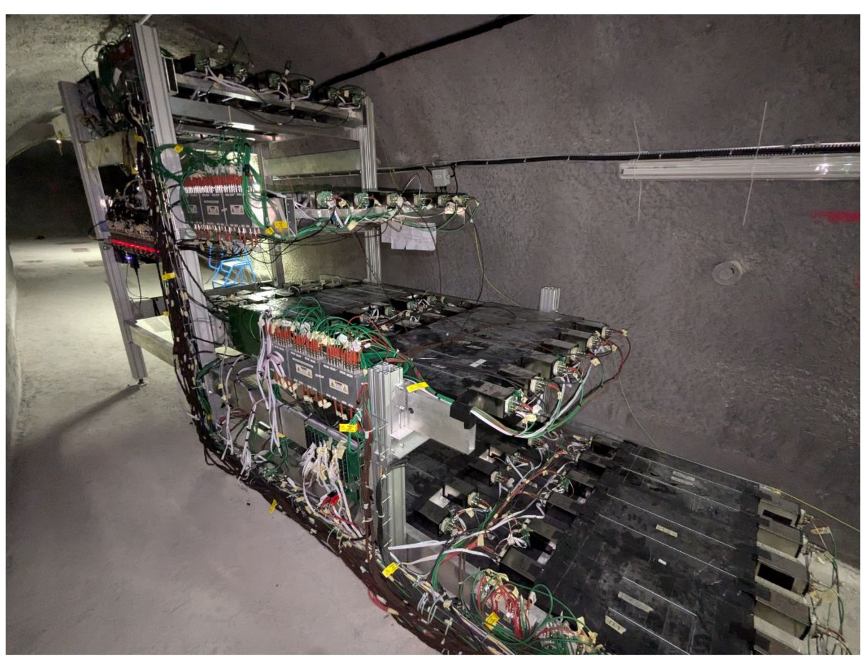
Results

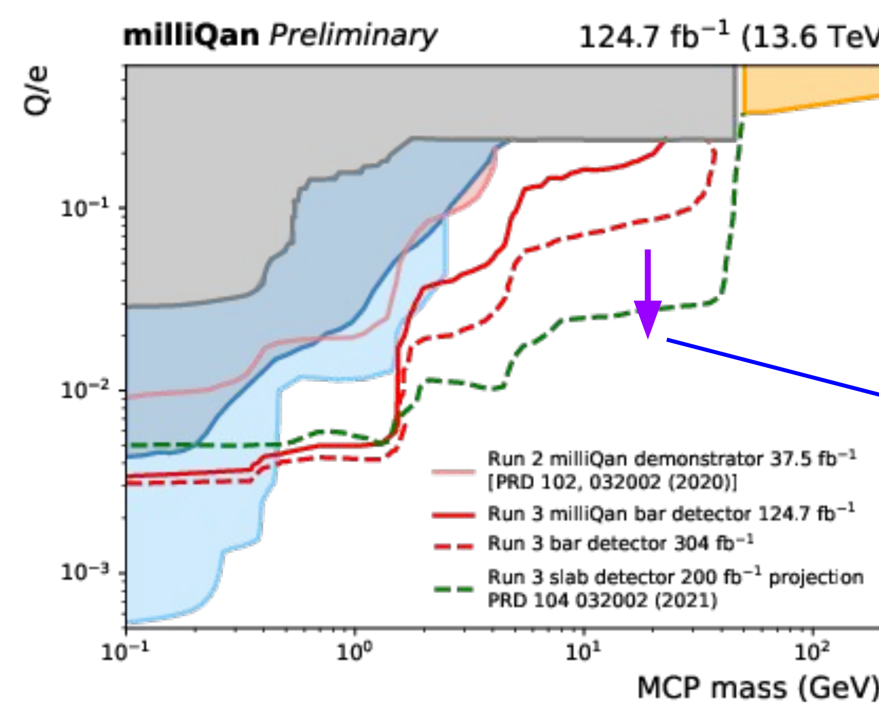
- **Most-stringent constraints** to date placed on mCP with charges < 0.24e and masses > 0.45 GeV
- We expect significant improvement with roughly 2x more data during Run 3!
- Recently installed complementary Slab detector to increase sensitivity in the high mass regime considerably!



Slab detector

- Four layers of 3x4 array of 40x60x5 cm^3 **slabs** with four PMTs for optimal light collection efficiency ➡ equivalent coverage of **1000** bars
- **Improved sensitivity** for mCPs with masses above 1.4 GeV due to increased acceptance
- Finished construction in Fall 2024 and currently recording physics data
- With its higher acceptance, slab detector is sensitive to other signals like sexaquark and fractionally charged particles from atmosphere (through the earth!)



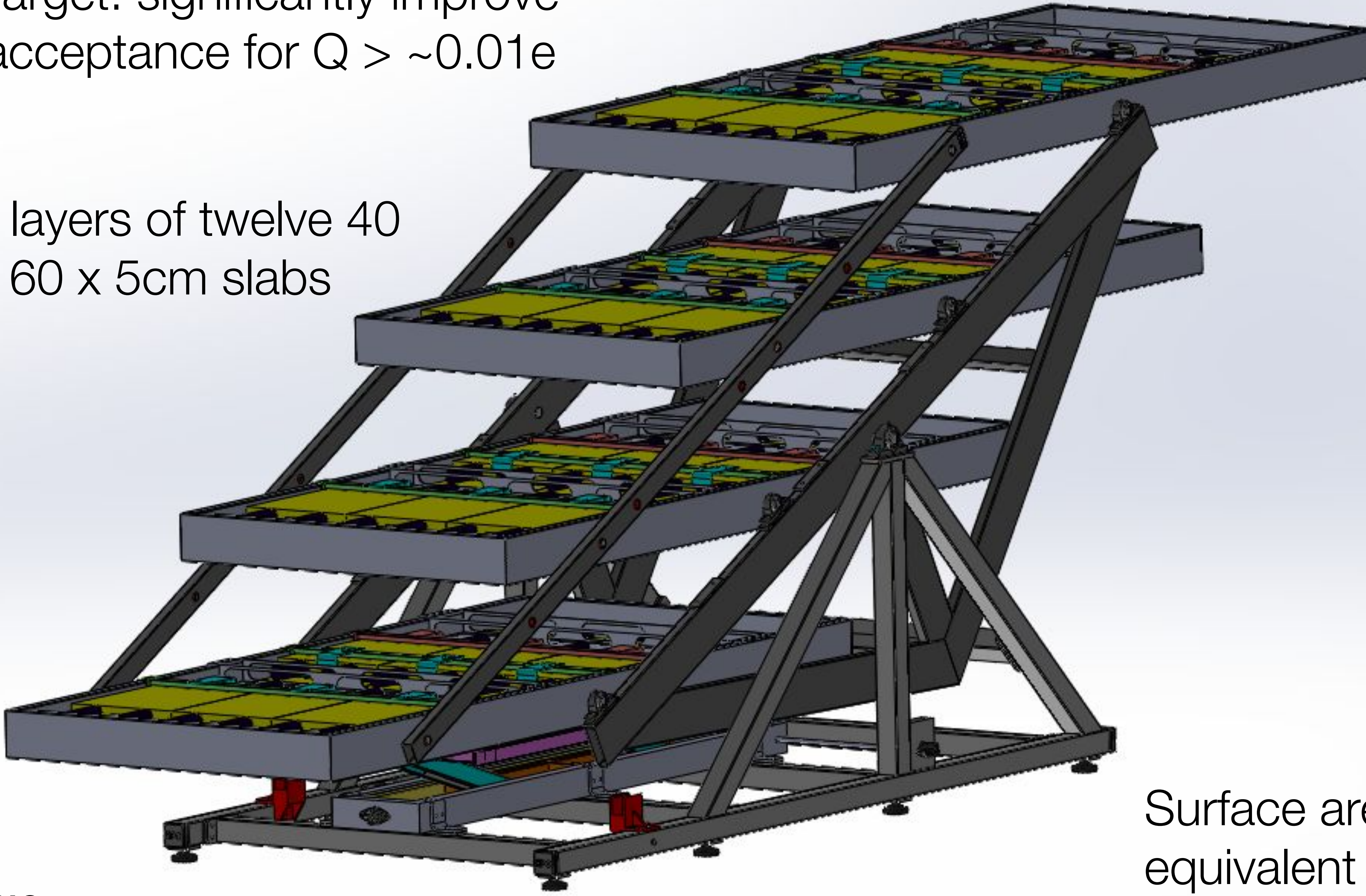


Run 3 slab detector
Improved sensitivity at high mass

Slab detector

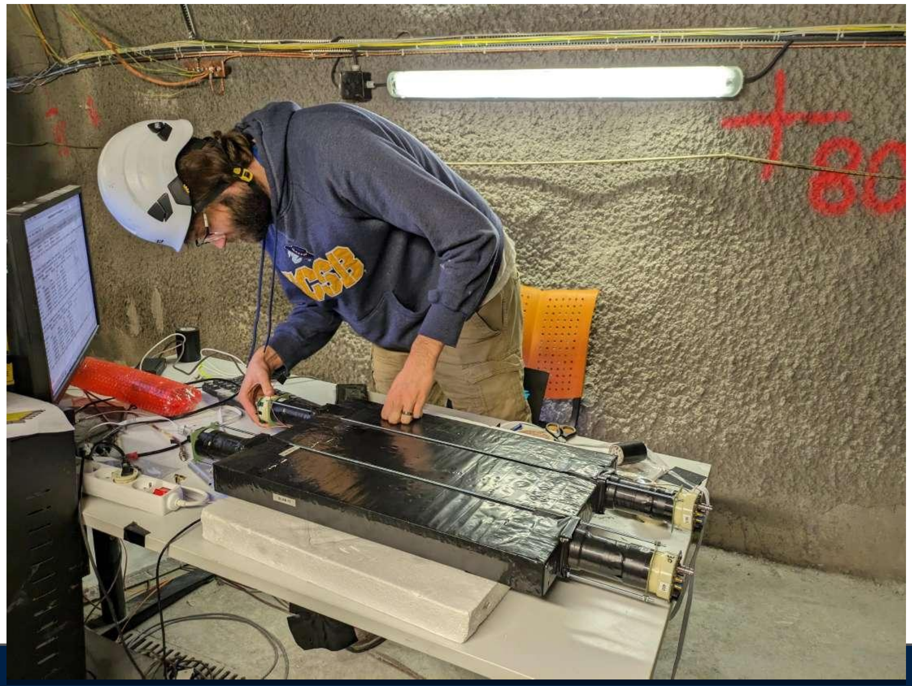
Target: significantly improve acceptance for Q > ~0.01e

Four layers of twelve 40 x 60 x 5cm slabs



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

Slab detector construction

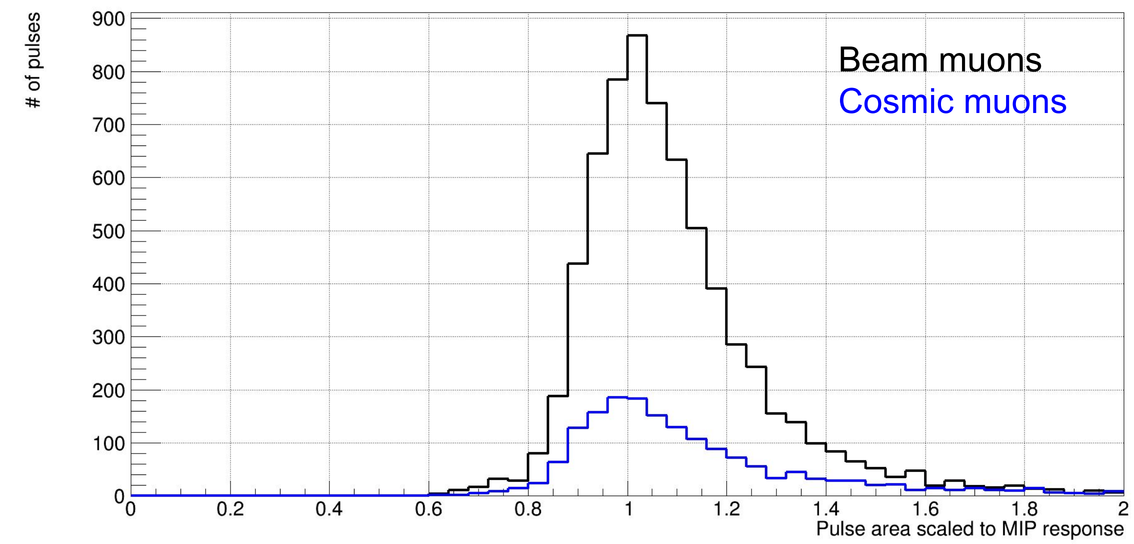


Slab detector installation finalized in July 2024 and smoothly taking data since October 2024

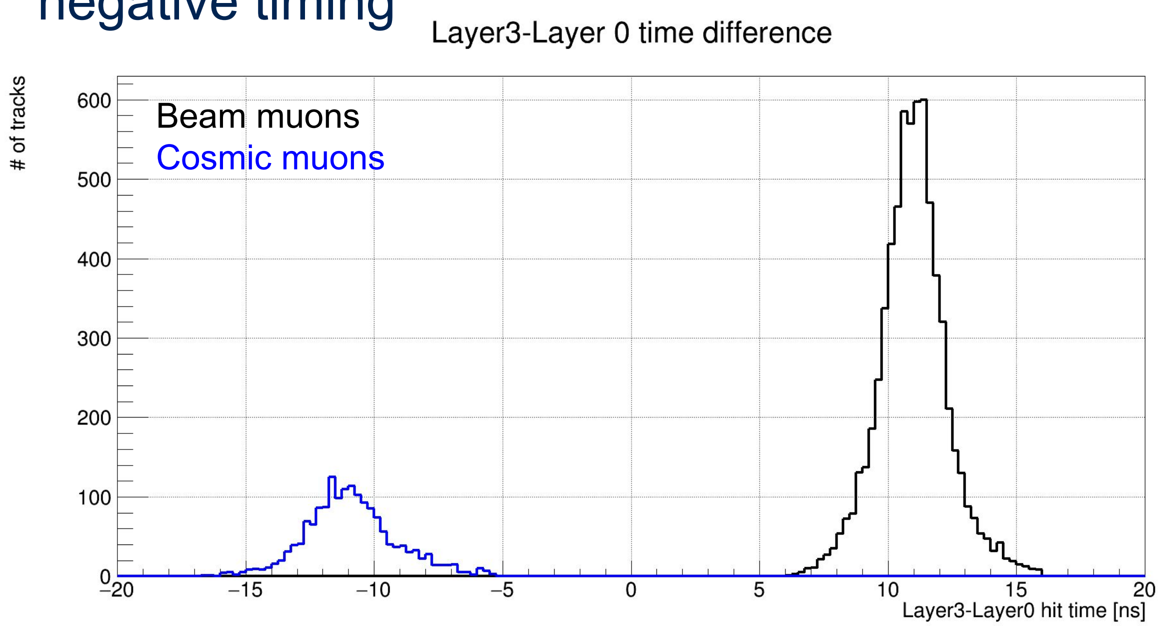
Slab detector commissioning

- Beam and cosmic muons are utilised for timing calibration
  - Timing of the downward going cosmics validate these calibrations!
- Individual channel sPE response and trigger validation underway

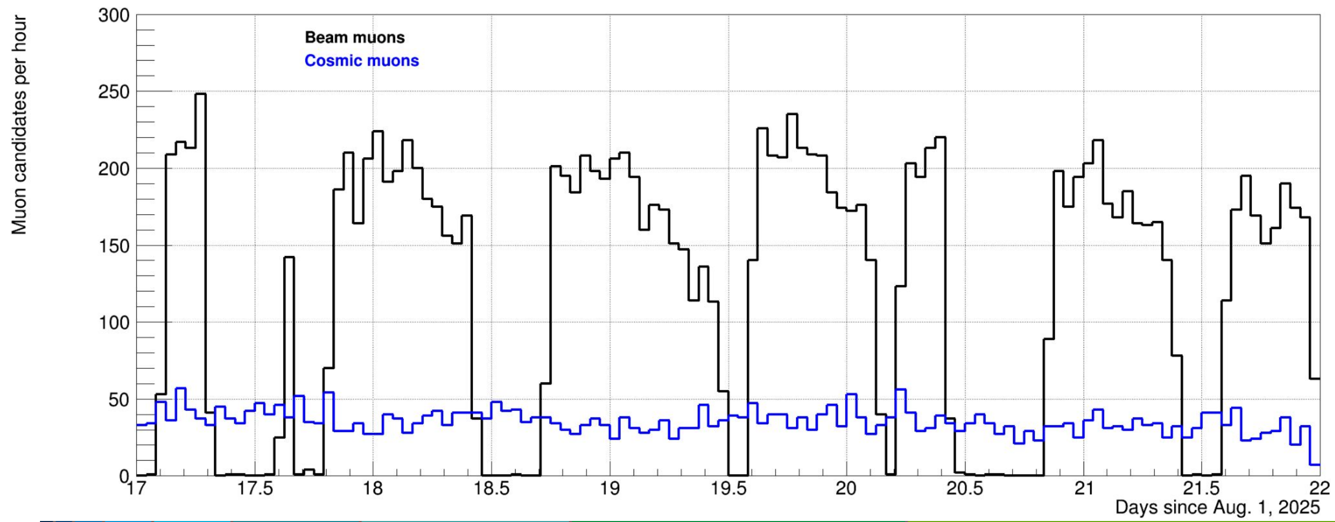
Response calibration: Pulse area of the beam muons and cosmic muons scaled to a MIP response



Timing calibration:The beam muons peak at a time difference consistent with particles from Interaction Point traveling at speed of light while downward going cosmics peak at equivalent negative timing

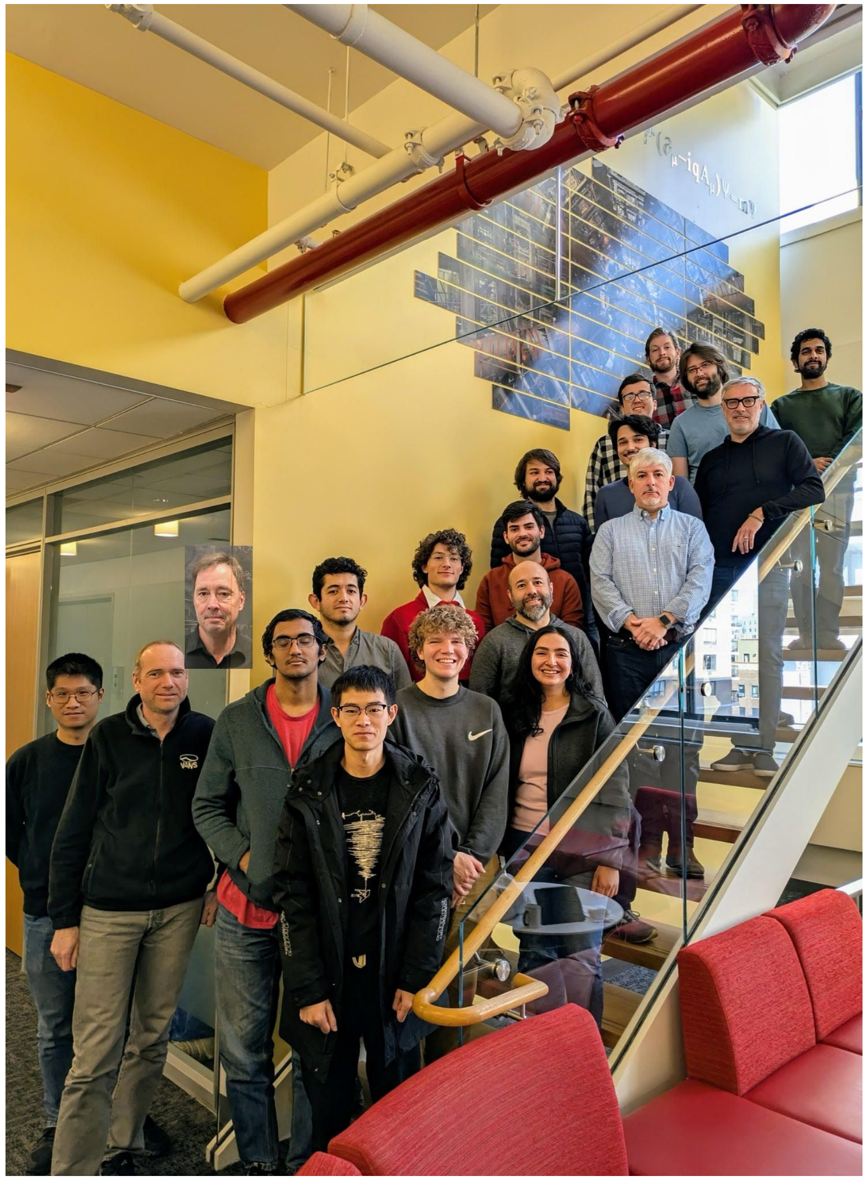


Monitoring: Rate of muons as a function of time. The beam muons follow expected pattern correlated with when the beam is on while cosmics show a constant



Summary

- MilliQan provides a highly sensitive model-independent probe for mCPs
- **First physics results using Run 3 dataset place world-leading limits on the mCPs with Q<0.24e and m<0.45 GeV**
- Run 3 physics program is robust and diverse with sensitivity to other long-lived particles
- Stay tuned for future results using full Run 3 bar detector data and the newly reconstructed slab detector



7th milliQan workshop, NYU, December, 2024

milliQan collaboration

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R. Loos,
A. De Roeck

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

M. Ezzeldine,
H. Zaraket,
M. Kamra

F. Golf
I. Reed
G. Zecchinelli

J. Brooke,
J. Goldstein

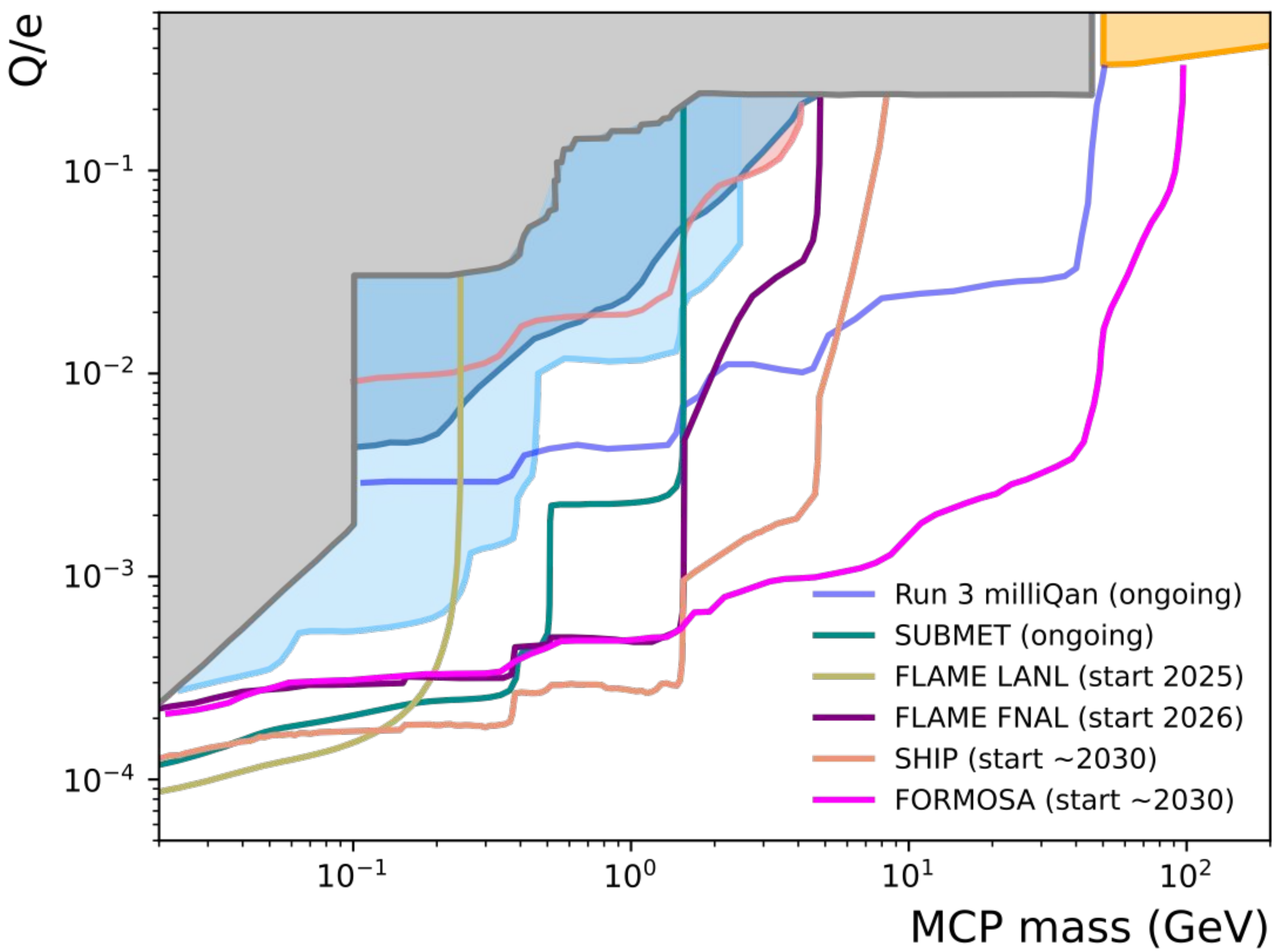
Backup

Event selection

Selection Criteria	Signal Region 1			Signal Region 2		
	Data Beam-On t=3393 h	Signal 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

A look into the future

very exciting time for millicharged particle searches!



- 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

Future!

Sources

FORMOSA: 2102.11493

SUBMET: 2007.06329

milliQan: 2104.07151

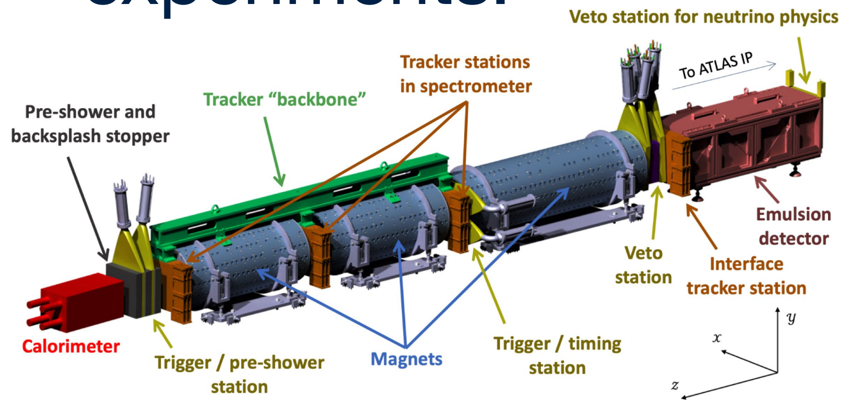
FLAME (at LANL): 2407.07142

SHIP-mQ: in preparation

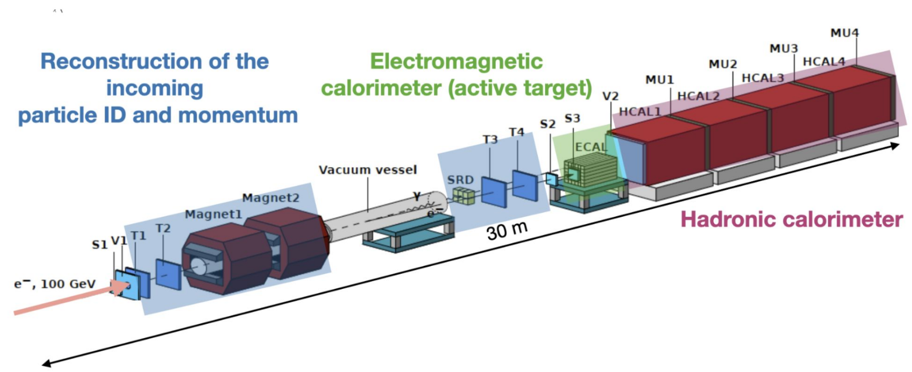
NB: MCP production in hadronic/EM showers, and proton brem. not yet considered - coming soon!

The hunt for Dark models

- Searching for hints of a dark sector is a key target of many experiments!



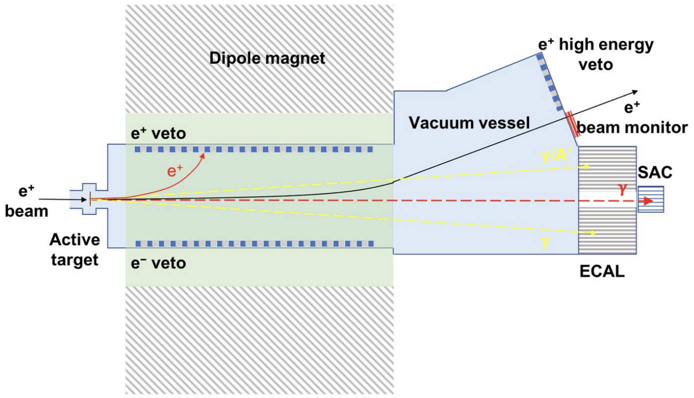
FASER@LHC



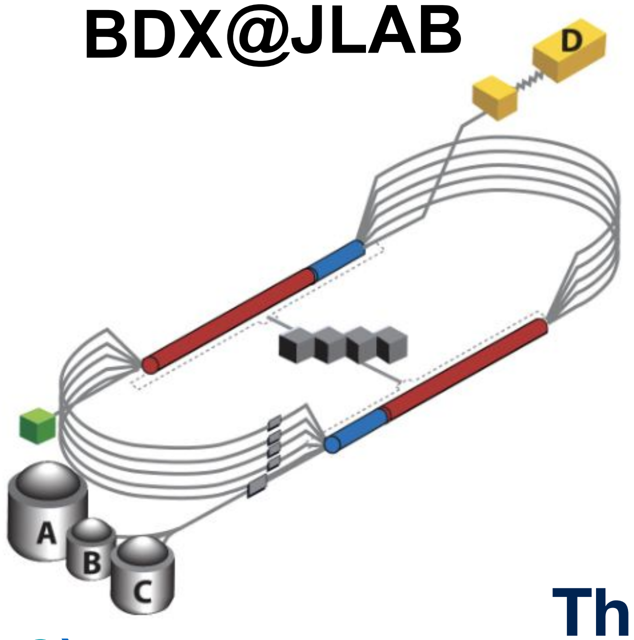
NA64@SPS

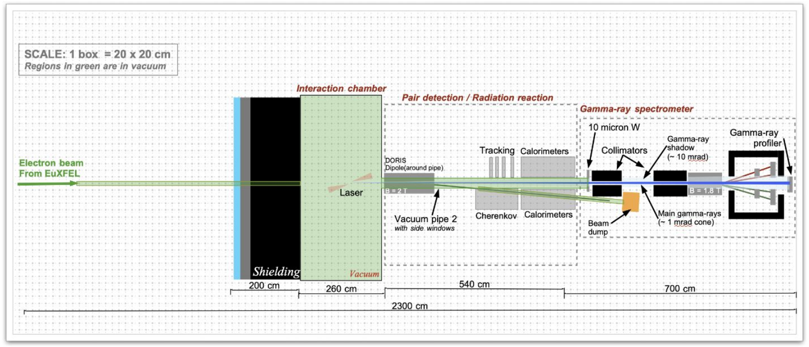
CCM@LANL

Multiple detectors: APEX, HPS, X17, BDX@JLAB



PADME@DAΦNE





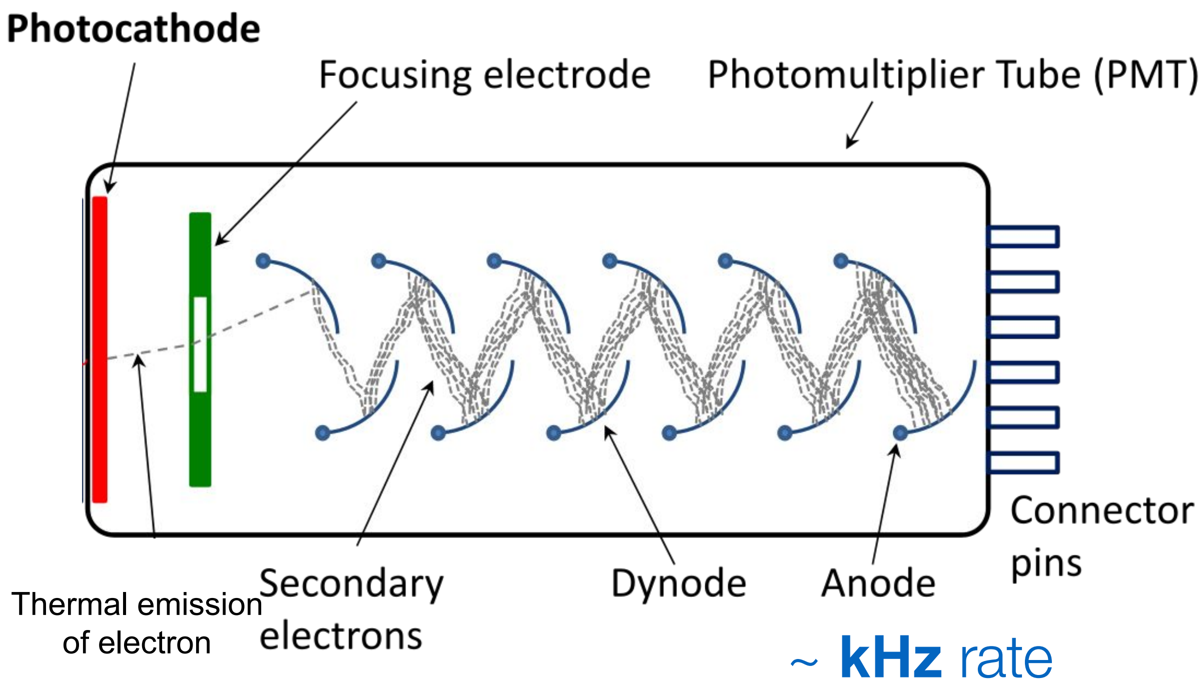
LUXE@DESY

+ CMS, ATLAS searches (recent CMS review: 2405.13778)

That's only a few of many more

Main background sources and vetos

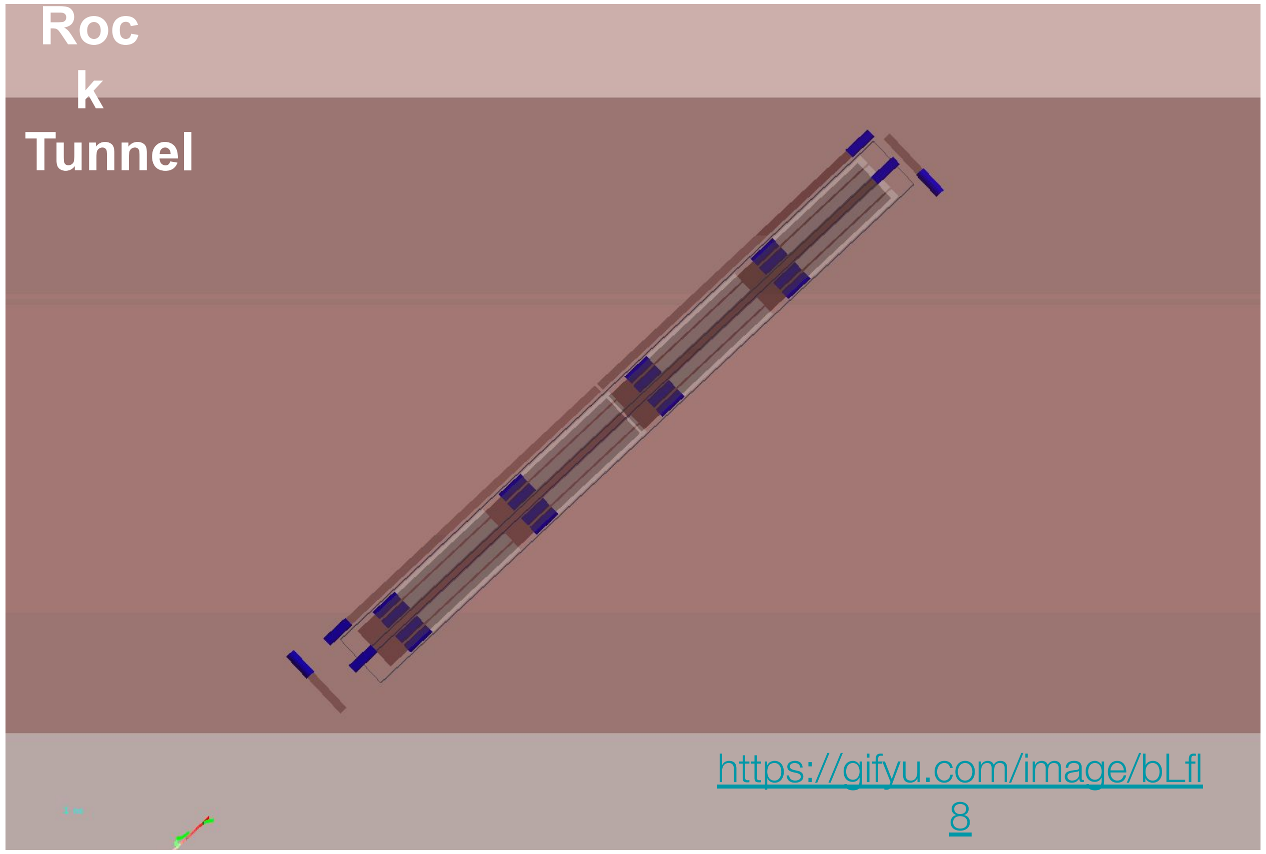
Background: PMT dark rate



~ **kHz** rate

Veto: hit in **each layer** within **20 ns window**

Background: beam/cosmic muon + secondaries



Veto: **single** deposit per layer forming **pointing path** to IP and **deposits in side panels vetoed**

Full range of selections reduce backgrounds by ~6 orders of magnitude (see backup)

MCP production

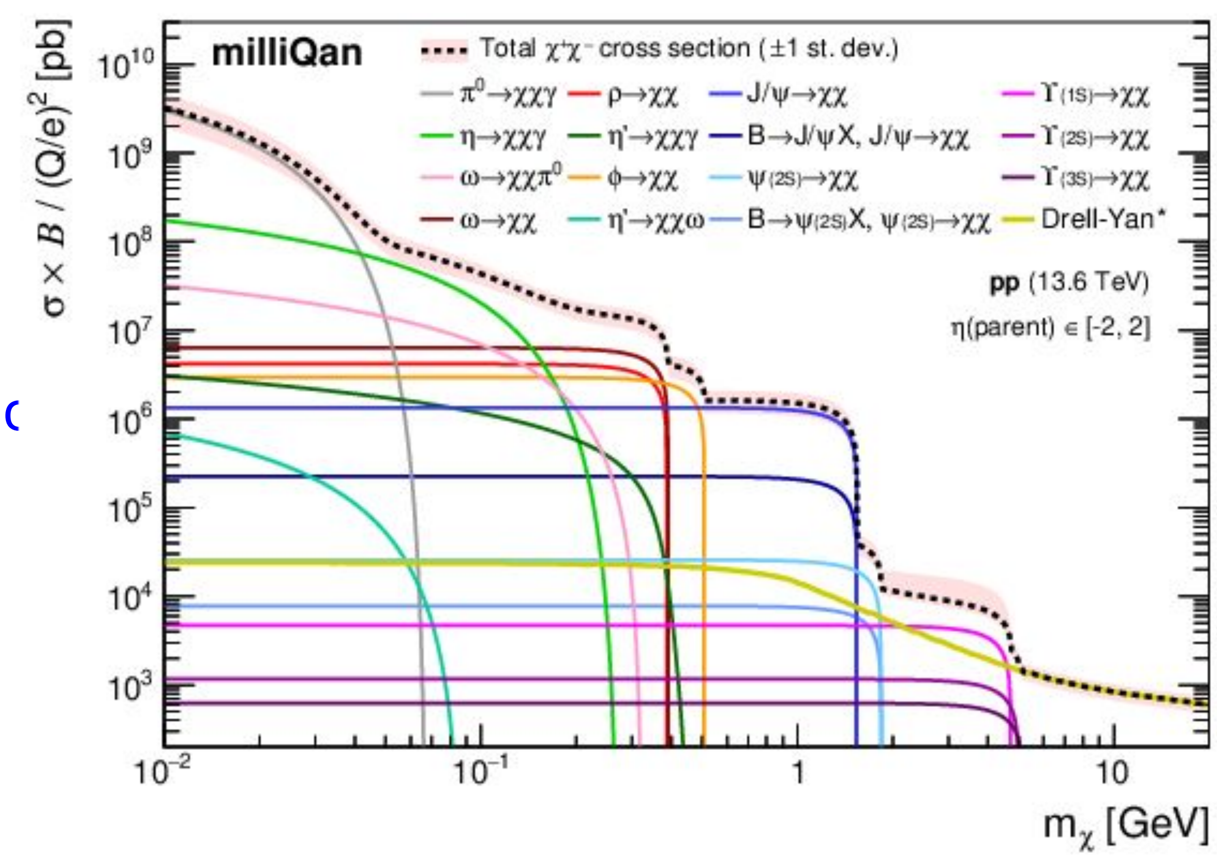
Consider dark sector containing U(1) abelian gauge field, A',

interacting with SM hypercharge B through kinetic mixing

$$\mathcal{L} = \mathcal{L}_{\mathrm{SM}} - \frac{1}{4} A'_{\mu\nu} A'^{\mu\nu} + i\bar{\psi}\left(\partial\!\!\!/ + ie' A\!\!\!/' - i\kappa e' B\!\!\!/ + iM_{\mathrm{mCP}}\right)\psi$$

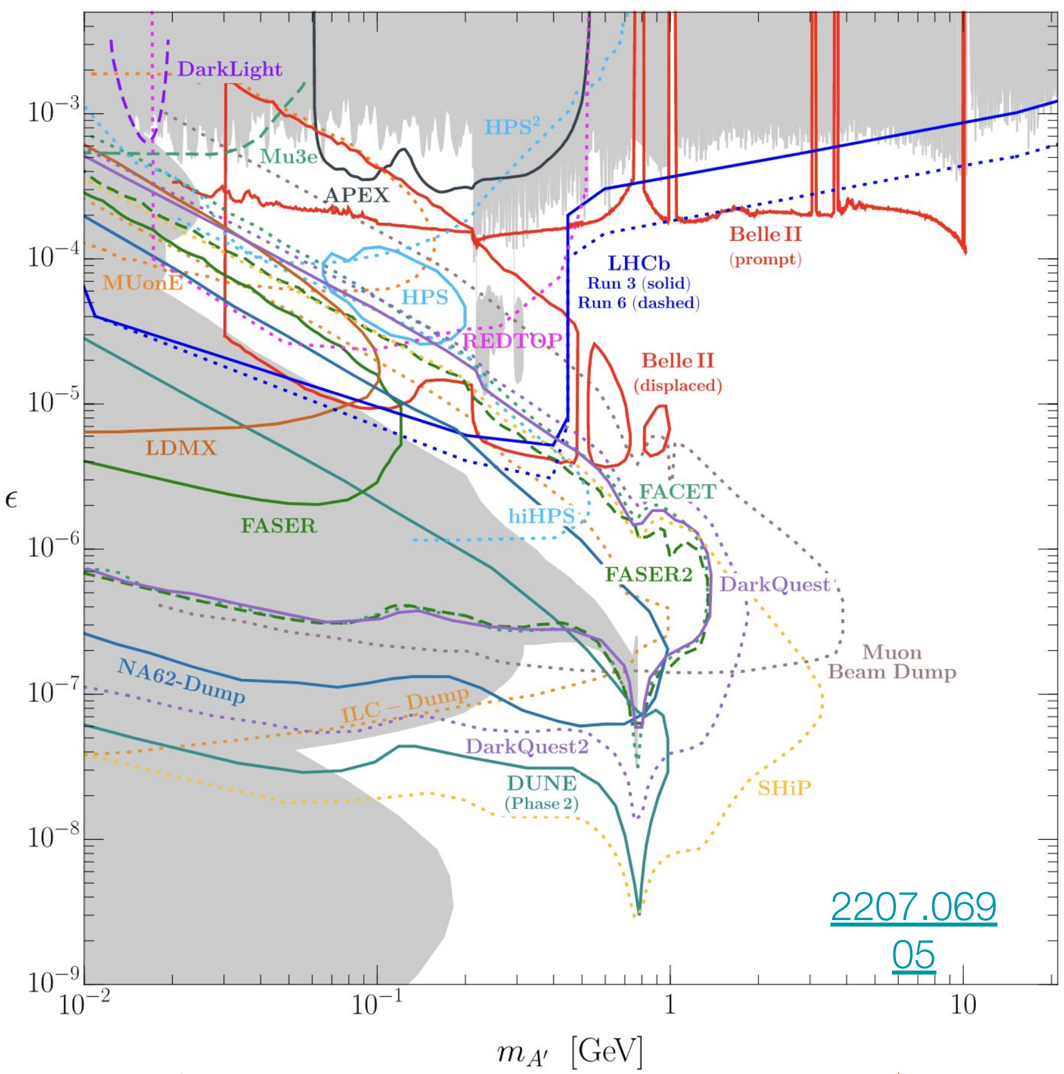
Results in a Dirac fermion with mass M_{mCP} and electric charge $\kappa e' \cos\theta_W$

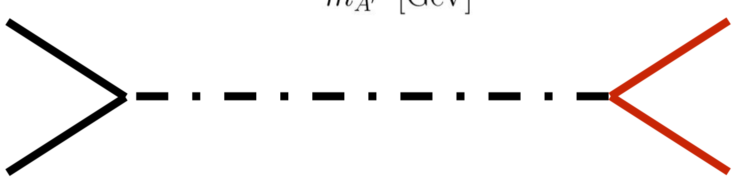
small ⇒ milli-charged particles (mCPs)



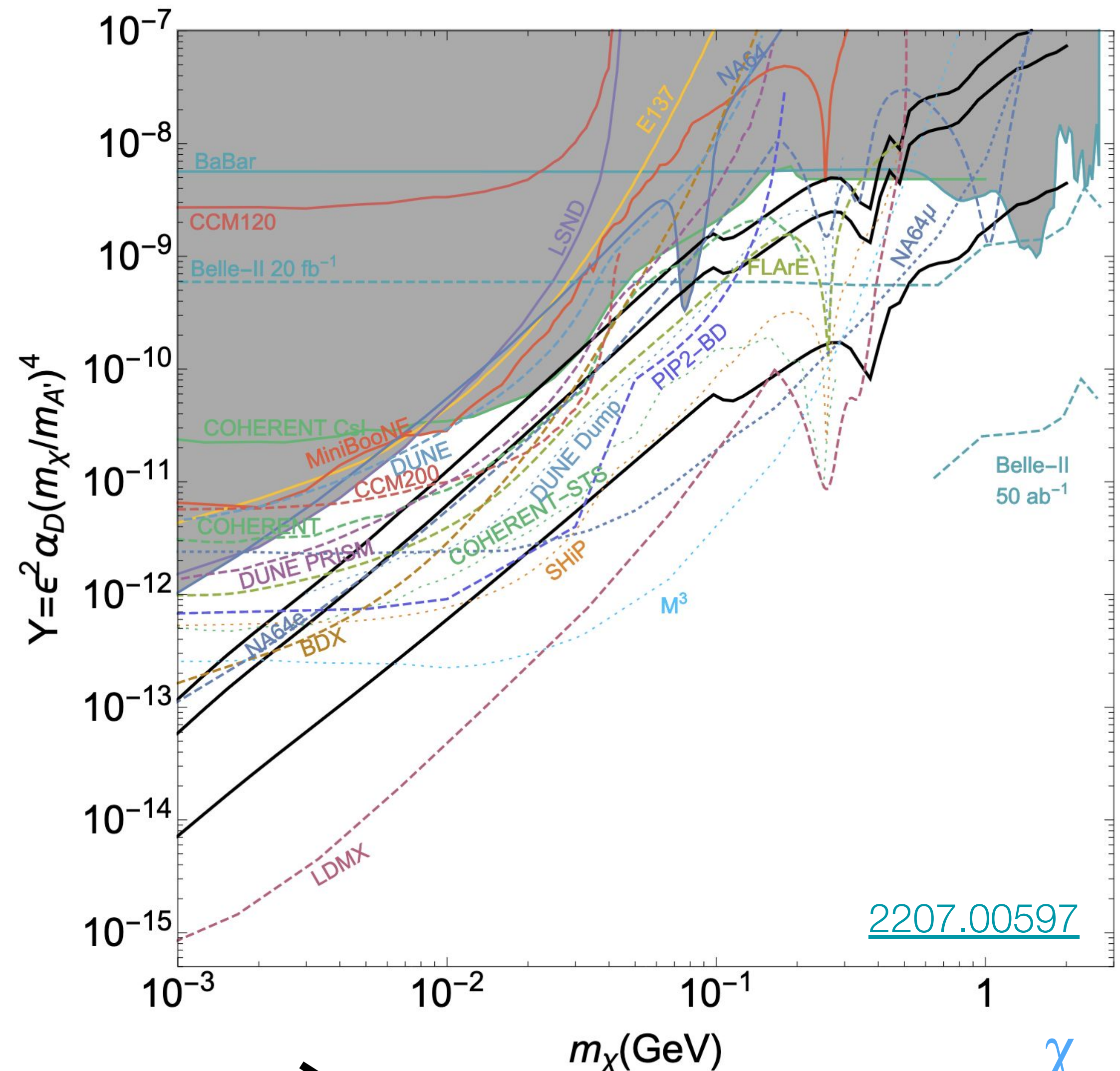
Any process that produces electrons at the LHC can produce mCPs!

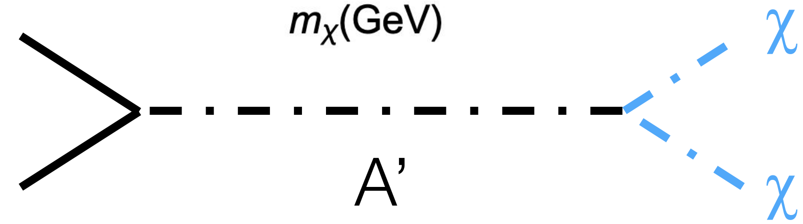
massive dark photon mediator



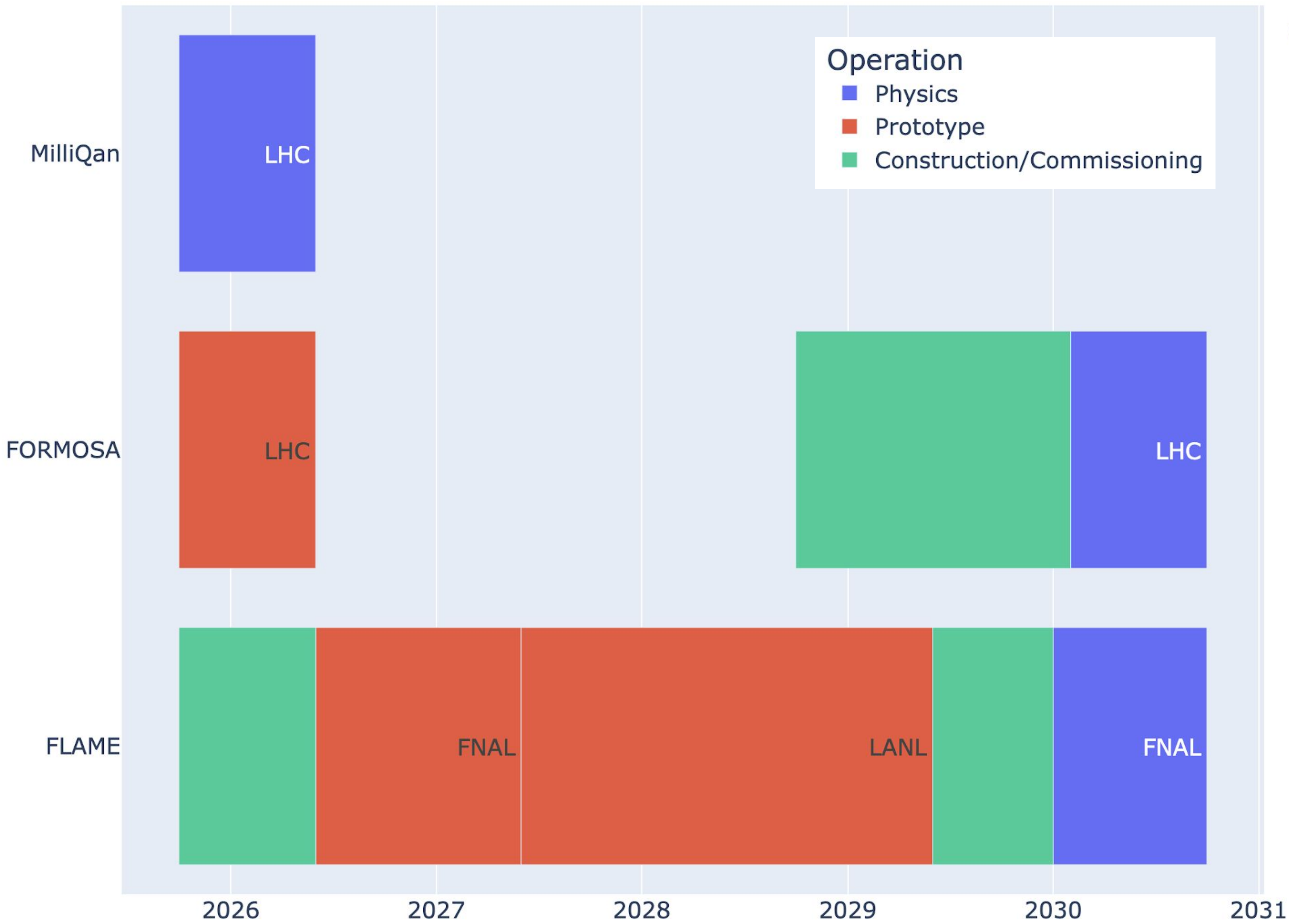


Dark photon undergoes (displaced) decay to visible particles





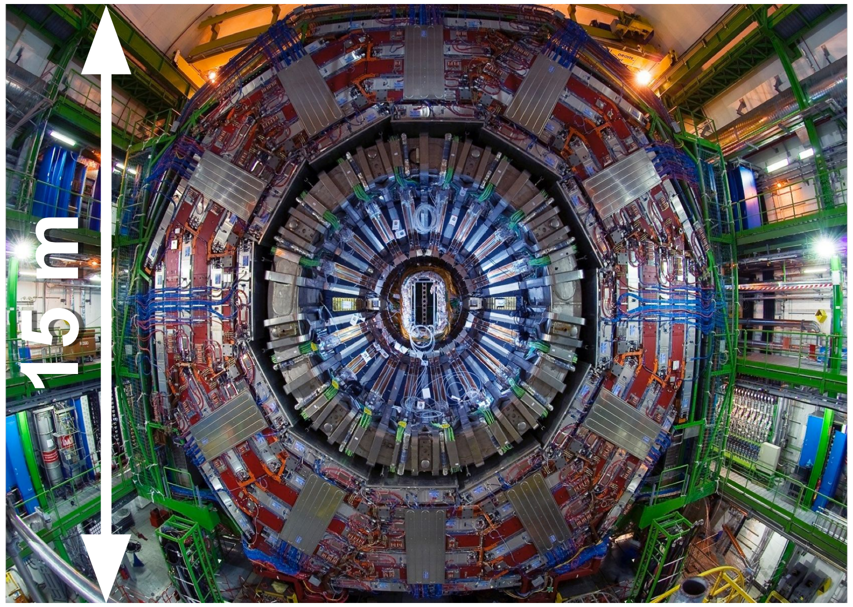
Dark photon undergoes decay to invisible particles



Operation
Physics
Prototype
Construction/Commissioning
MilliQan
FORMOSA
FLAME
LHC
LHC
LHC
FNAL
LANL
FNAL
2026
2027
2028
2029
2030
2031

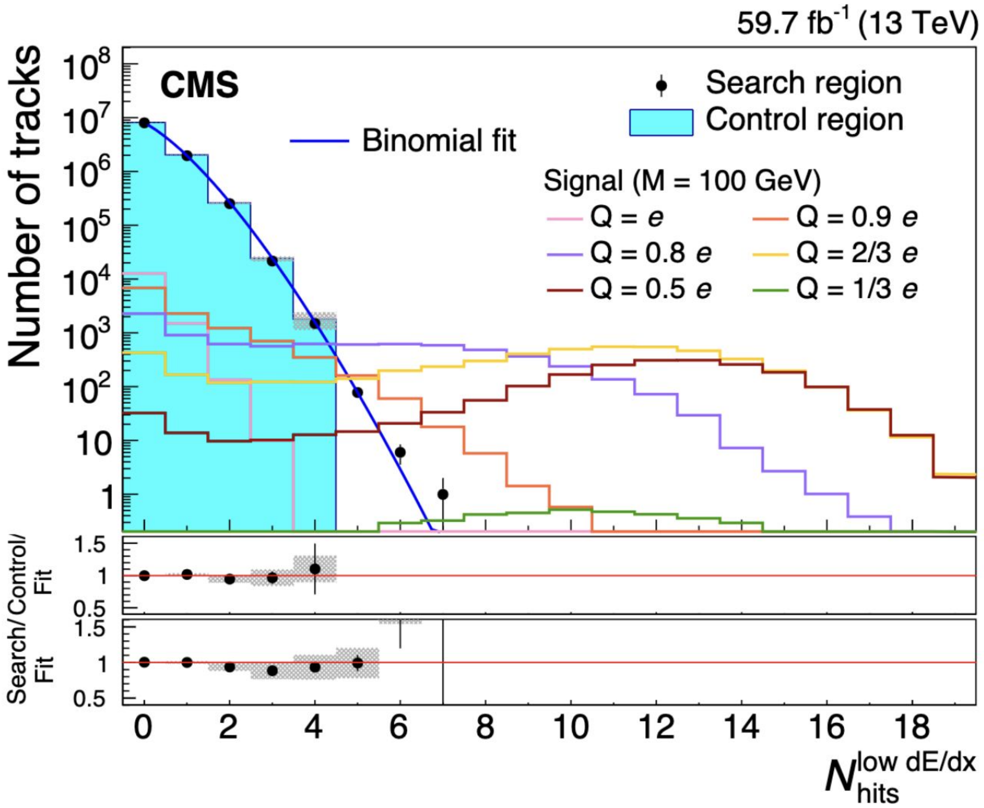
What can CMS do?

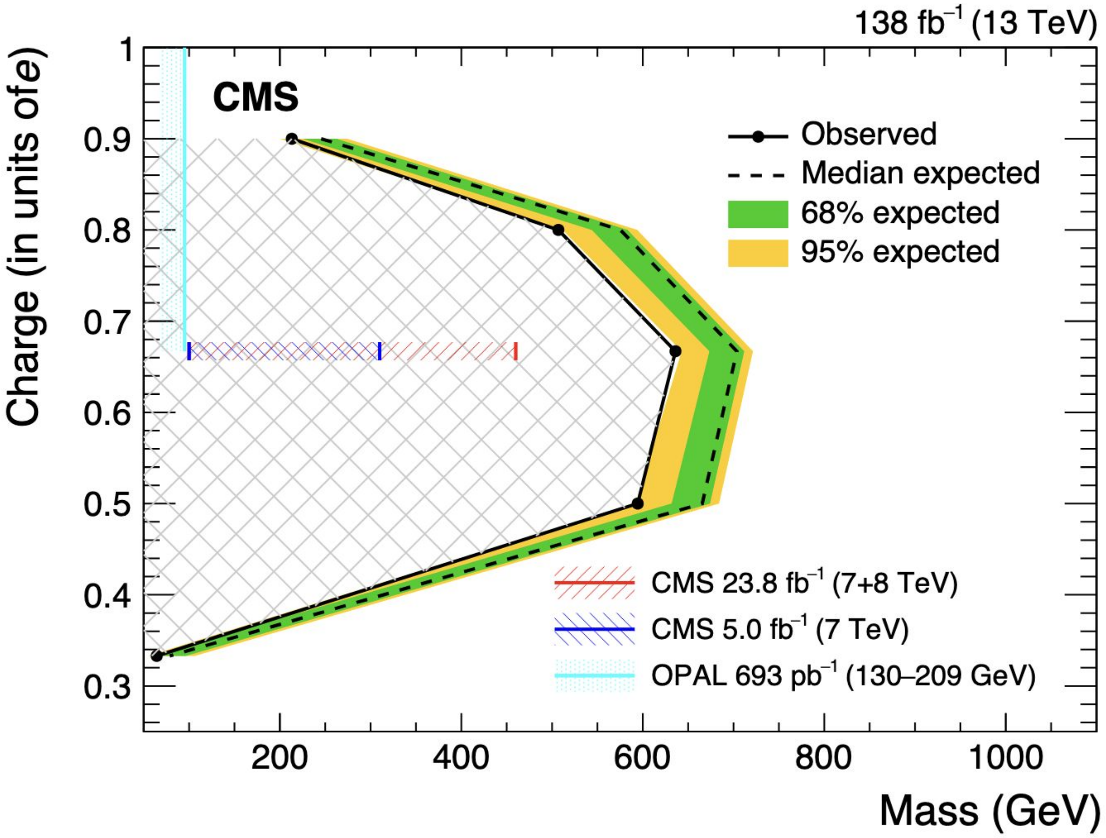
- Low dE/dx hits in the tracker provides **sensitivity down to Q ~ 0.3e**
- Below this not enough energy is deposited in the detector to allow reconstruction



CMS: general purpose detector at the LHC

MCP energy deposition

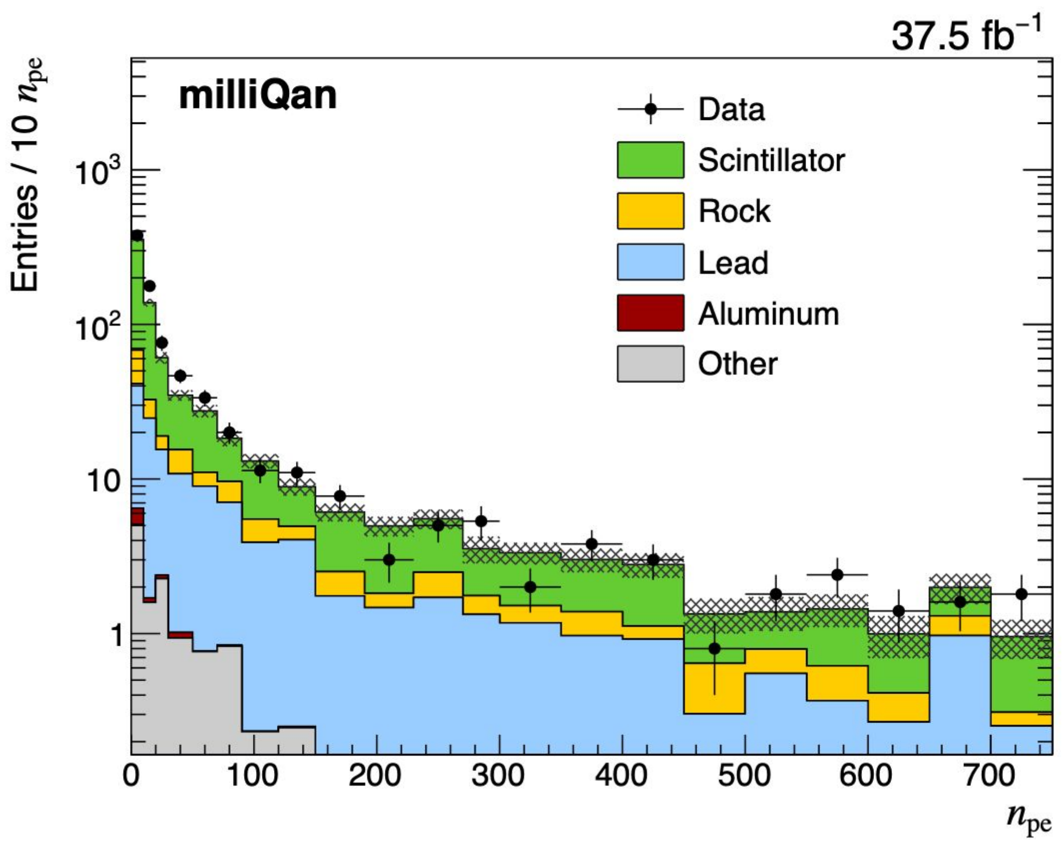




Fractionally charged particle search EXO-19-006

Detector simulation

- Full **GEANT4 simulation** of milliQan demonstrator for signals and backgrounds
- Models reflectivity, light attenuation length and shape of scintillator
- Incorporates separate calibration for **each scintillator+PMT module**
- Comparison of muon showers in data and simulation shows good agreement across a wide range of energy depositions



Number of PE deposited in bars from muon shower products

Full background rejection

SR1

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)

SR2

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)

Muon production and propagation