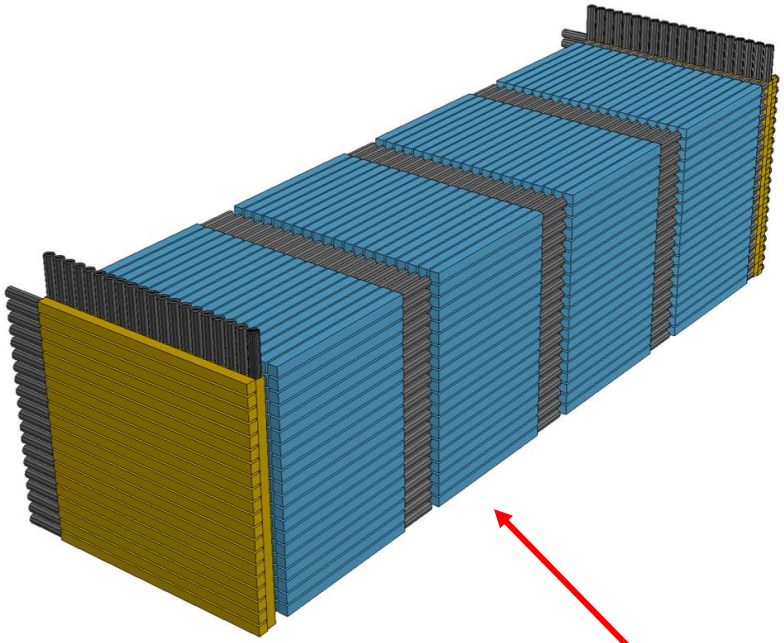
Looking forward to millicharged particles at the LHC

Jacob Steenis on behalf of the
FORMOSA Collaboration

The FORMOSA Detector

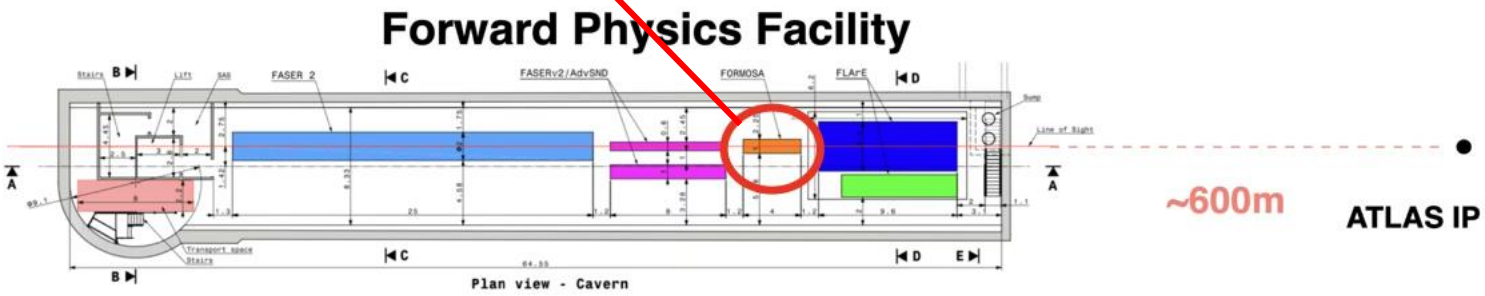


The design:

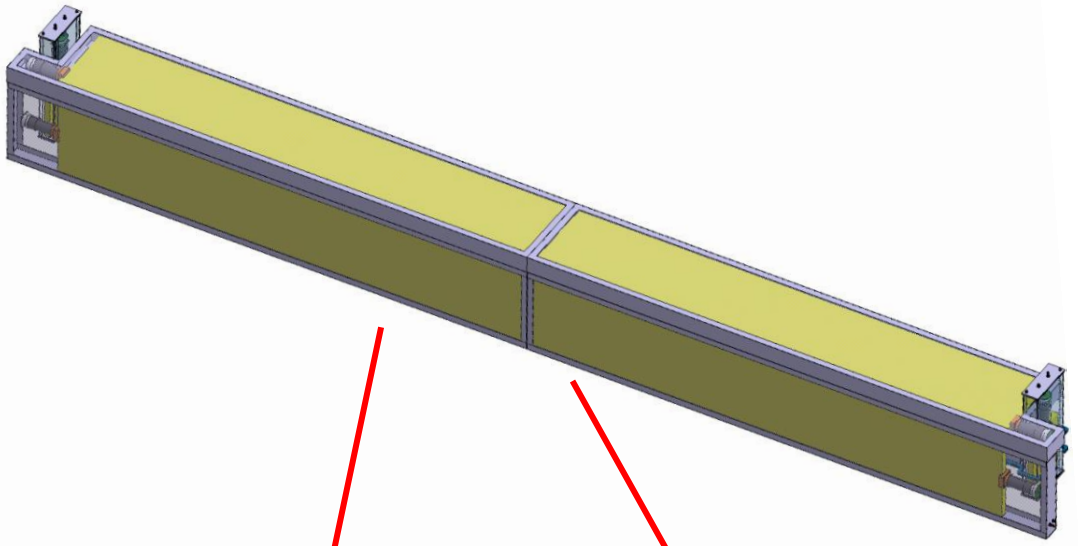
- 20 x 20 x 4 array of plastic scintillators coupled to photomultiplier tubes
- Hodoscope on the front and back of detector for muon identification

Benefits from location:

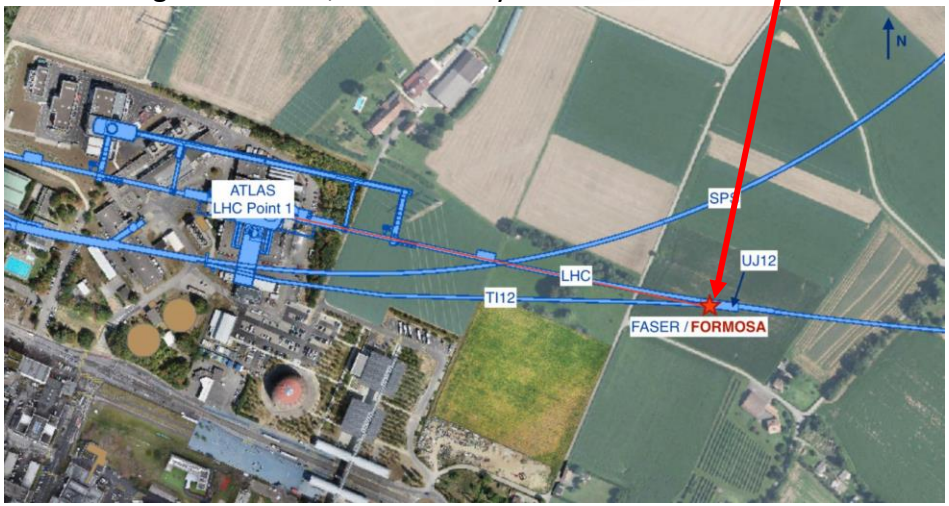
- ~250x enhancement in millicharge flux relative to central region
- Rock shielding (~600m) from particles produced at ATLAS



The FORMOSA Demonstrator



Forward region of ATLAS, ~500m away.



Growing over the last couple years

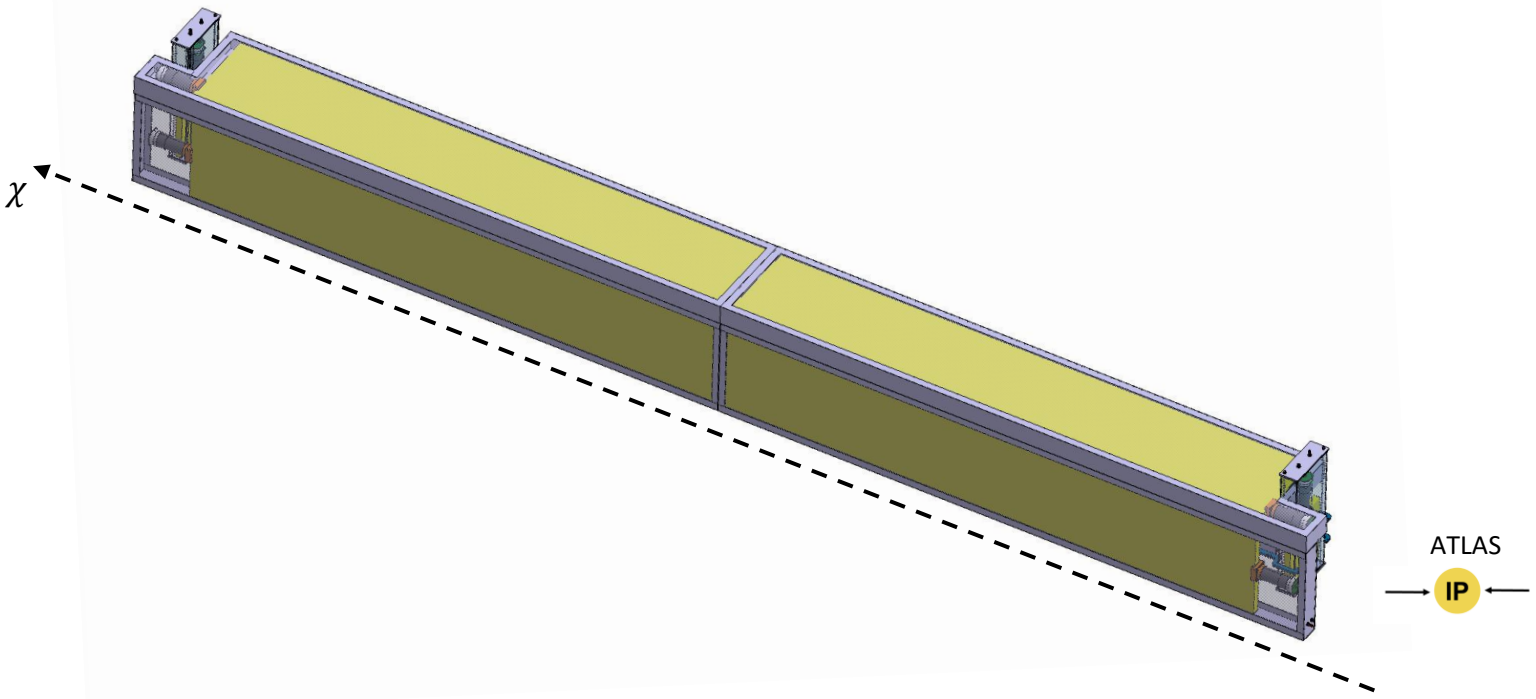
(Feb 2024)

(June 2024)

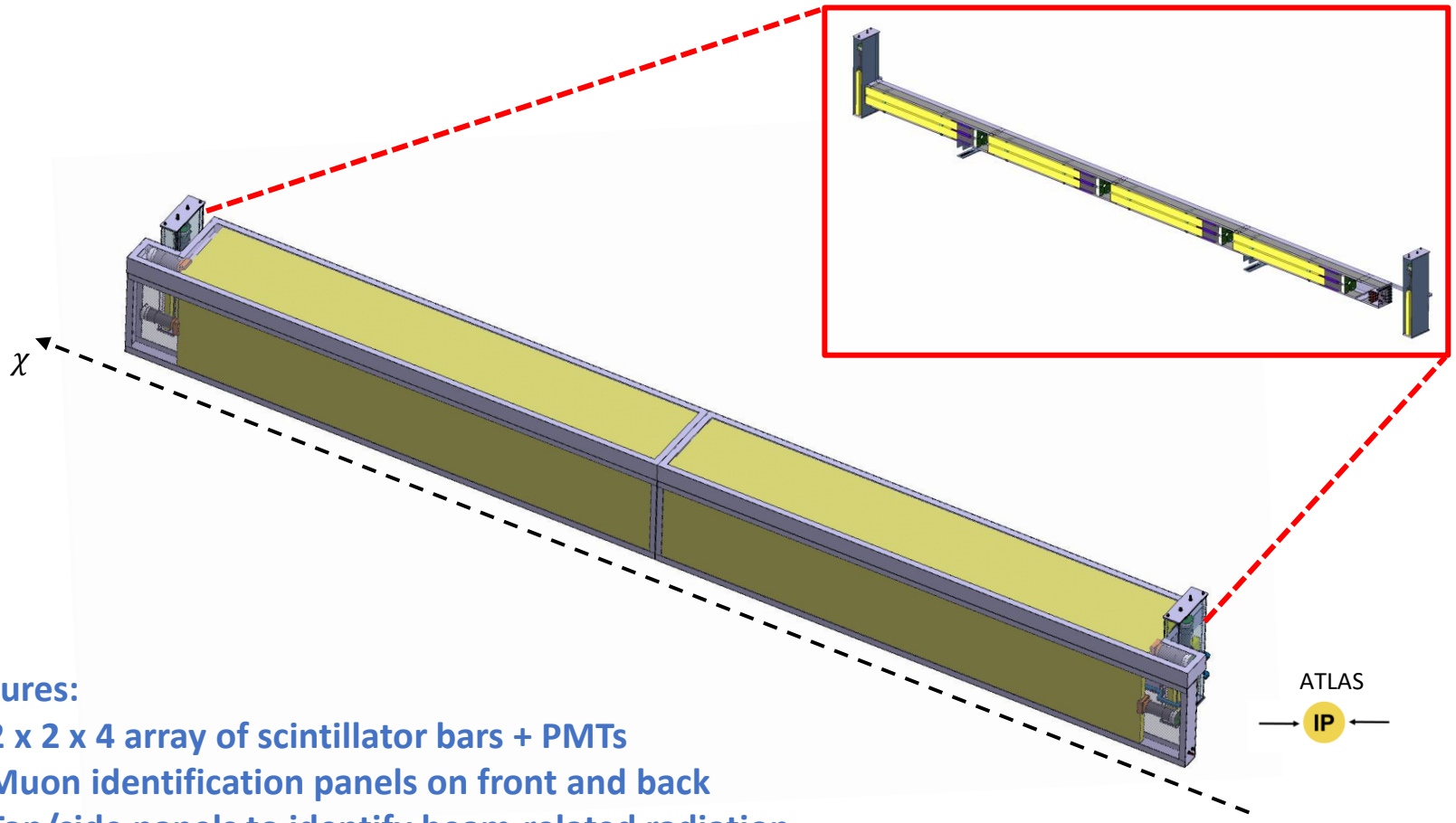
(Feb 2025)

LHC clock and orbital signals were also funneled into the DAQ during 2024 running…

The FORMOSA Demonstrator



The FORMOSA Demonstrator

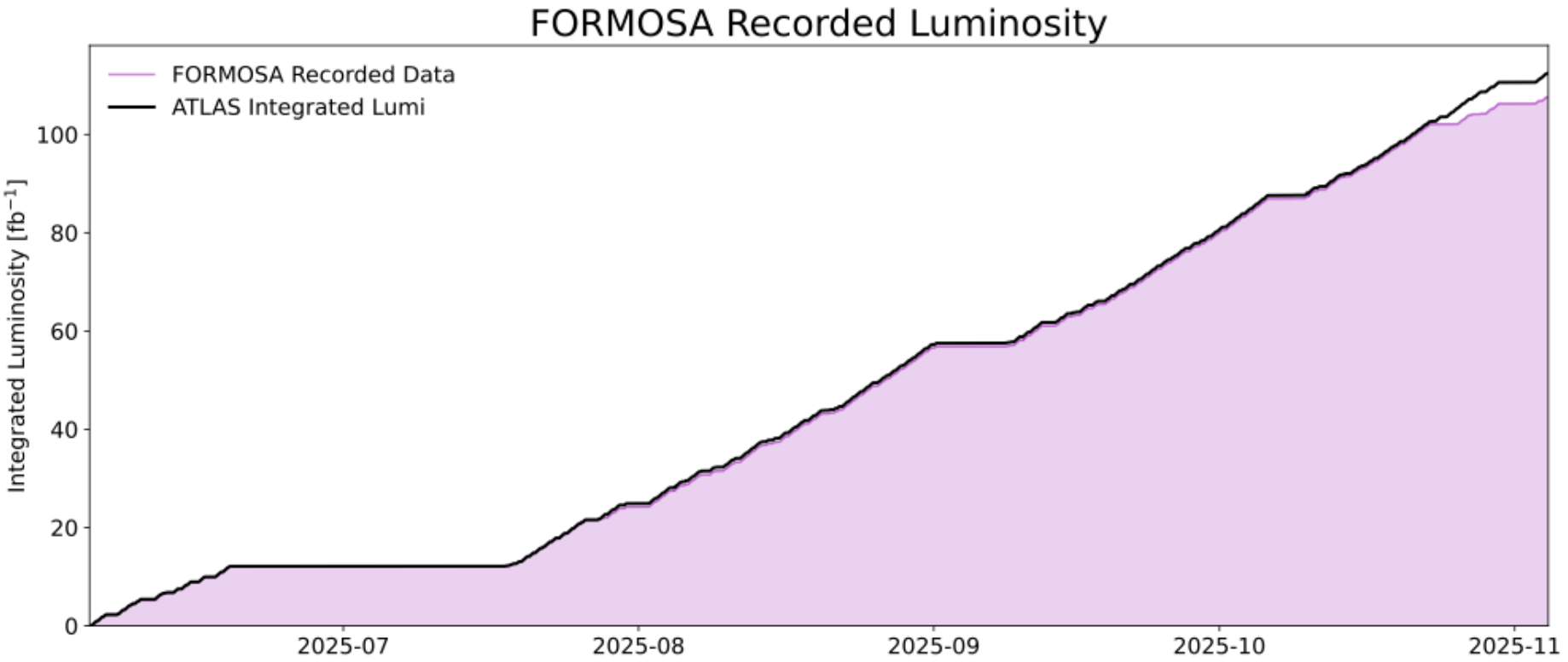


Features:

- **2 x 2 x 4 array of scintillator bars + PMTs**
- **Muon identification panels on front and back**
- **Top/side panels to identify beam-related radiation**

Signal-like event: ***small deposits in a row in all four layers within a short time window***

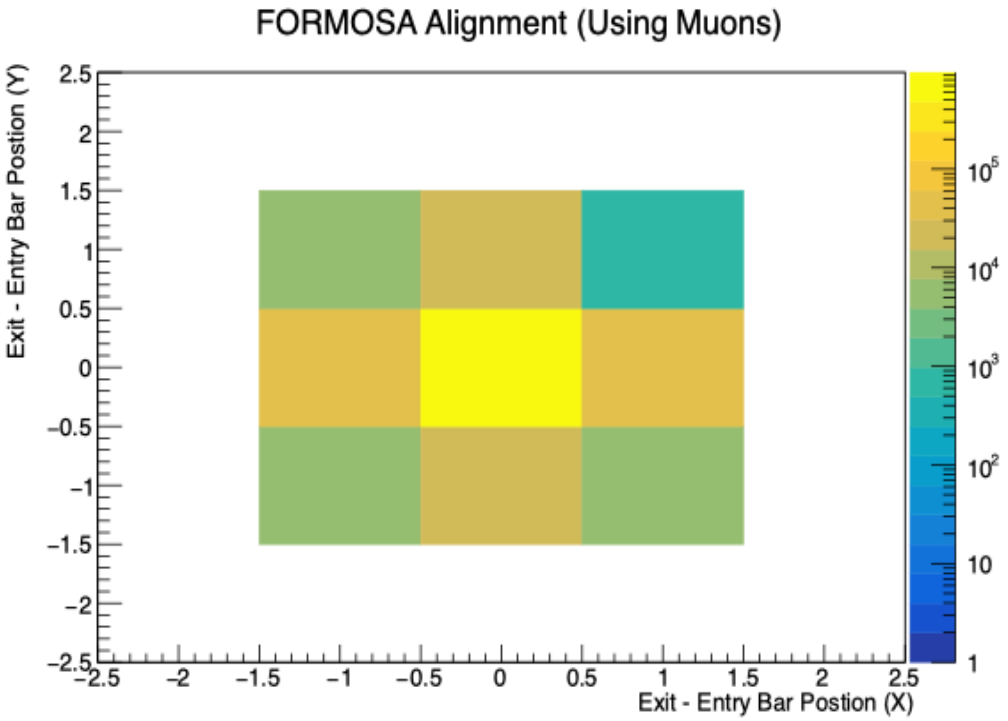
Data collection 2025

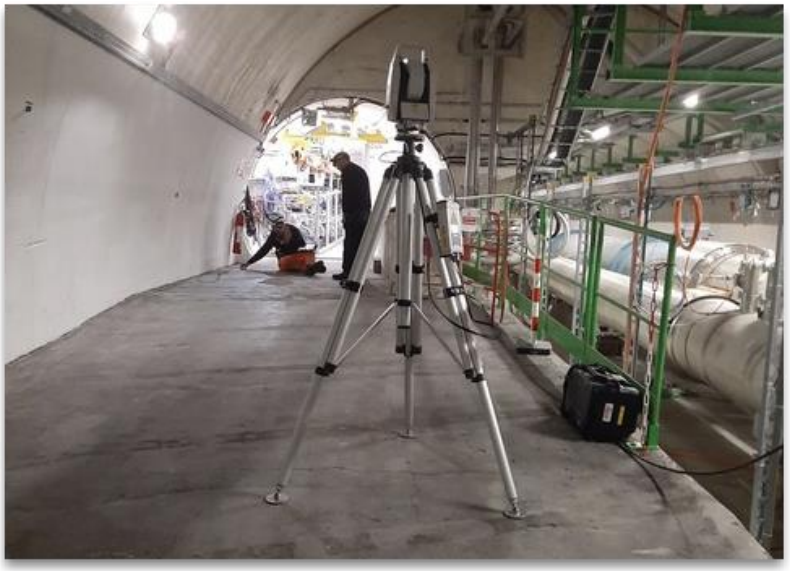


~100 fb^{-1} of analysis-quality data from 2025

("Losses" come from special data runs)

Data collection 2025

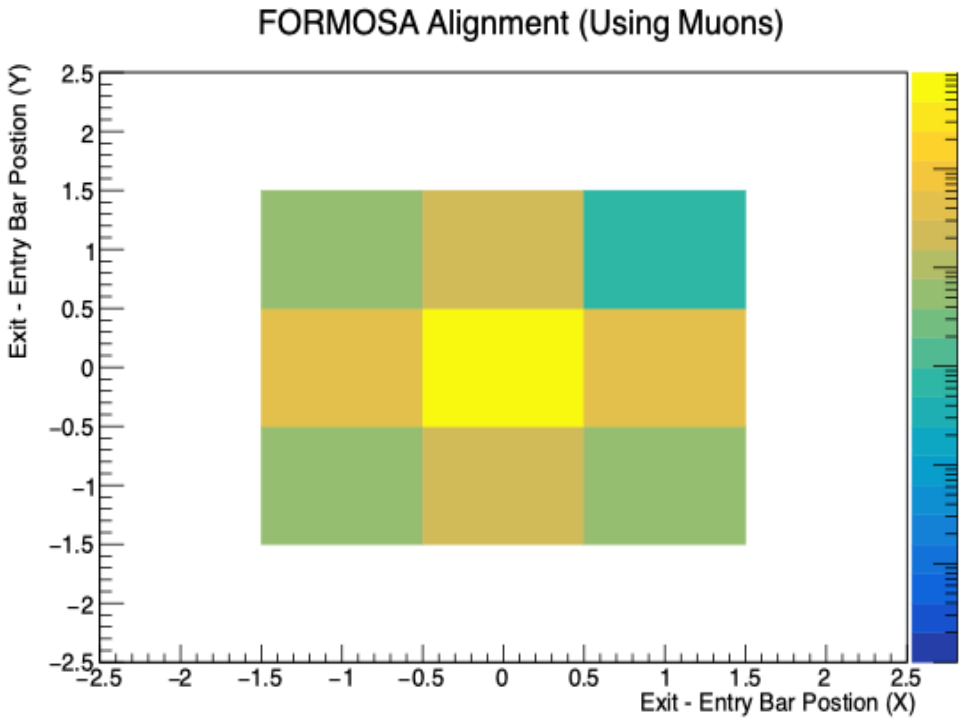




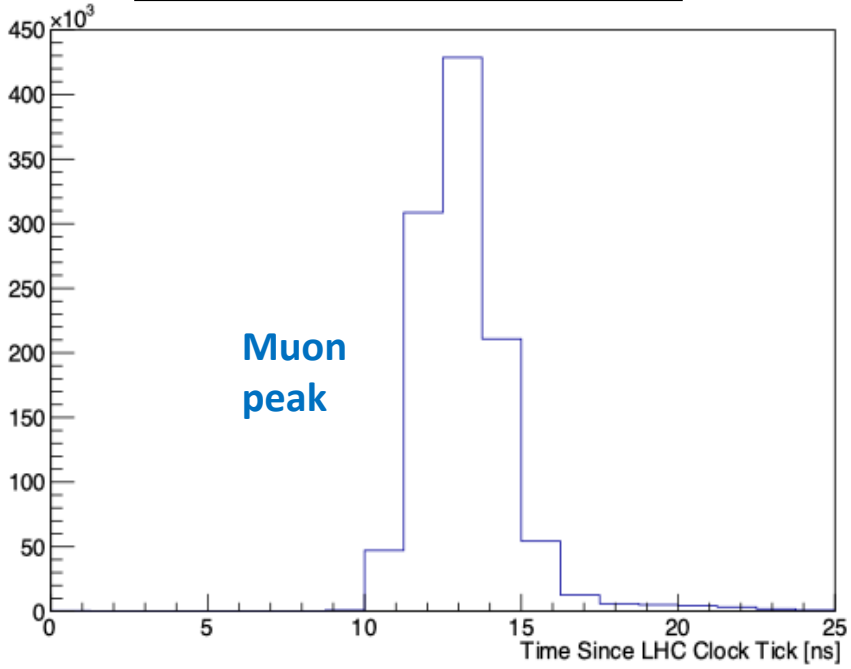
Detector was aligned by the CERN Survey Team.

We can confirm alignment using muons produced at ATLAS

Data collection 2025

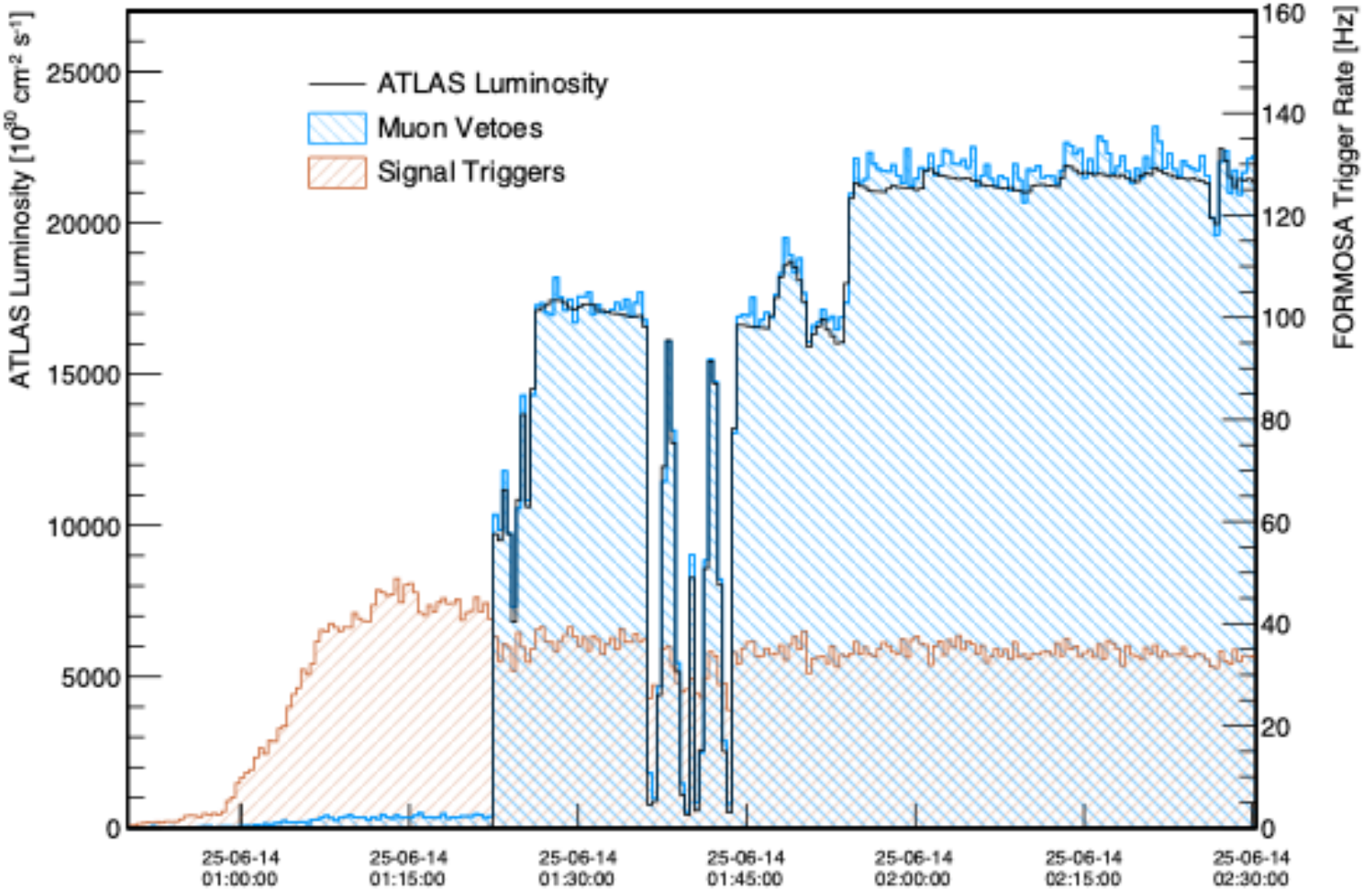


Time within LHC Clock Ticks



We can also see muons tightly peaked within the LHC clock period, like FASER

Data collection 2025



FORMOSA triggers align well with the activity at the LHC!

Now, let’s get into the exciting new things...

The real problem with muons…afterpulsing

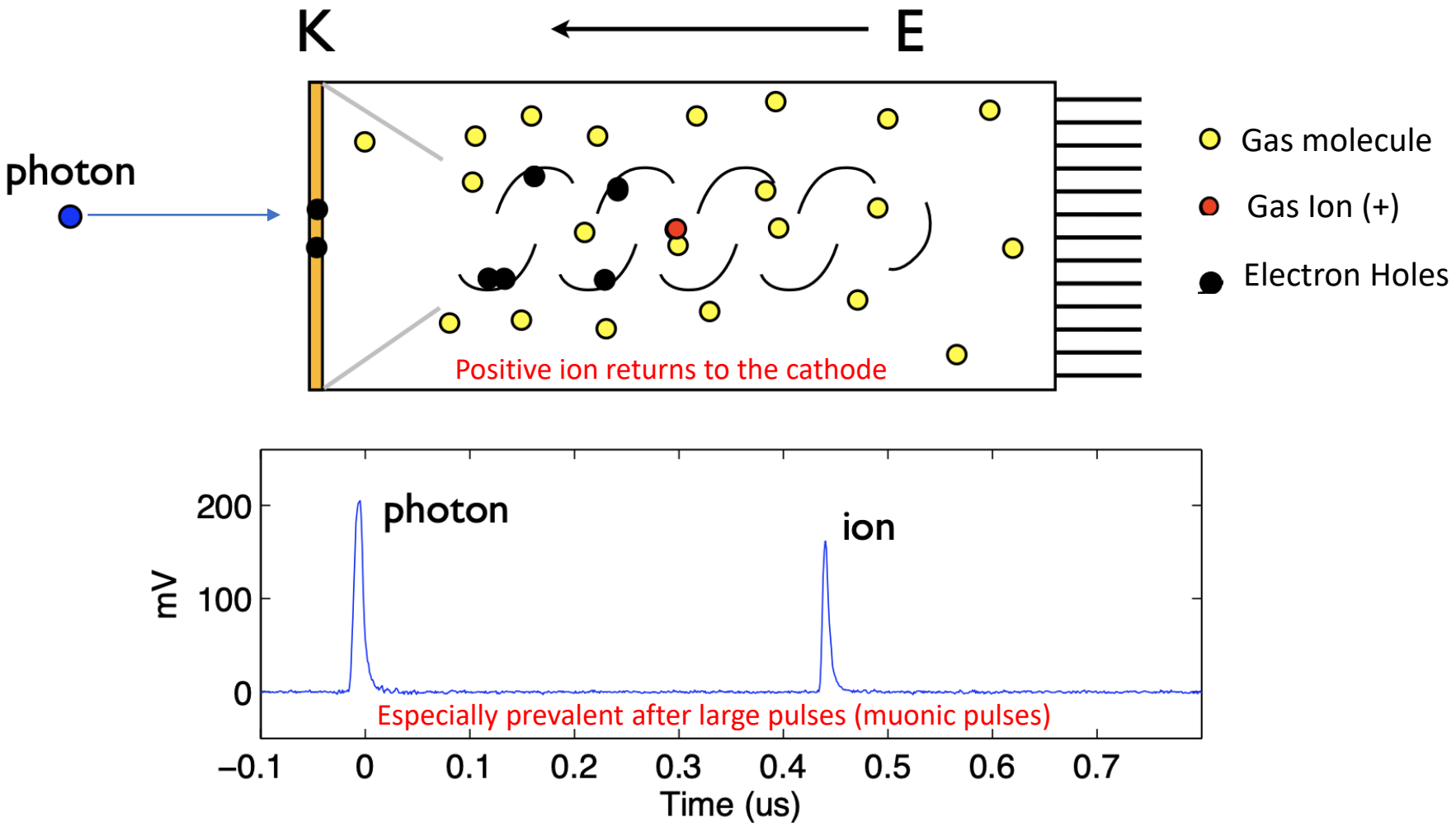


Diagram and plot: Carlos Hernandez Faham

The real problem with muons…afterpulsing

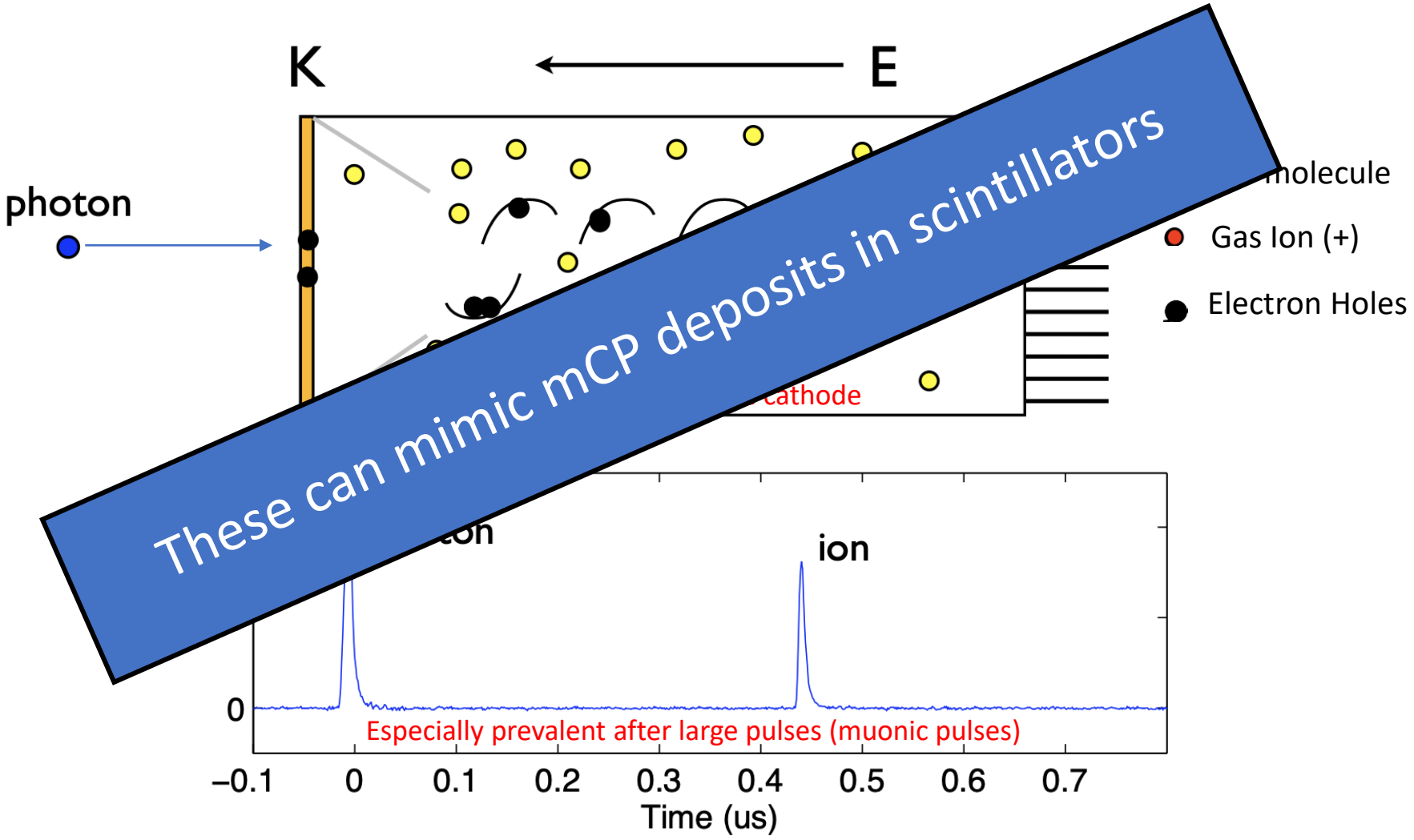
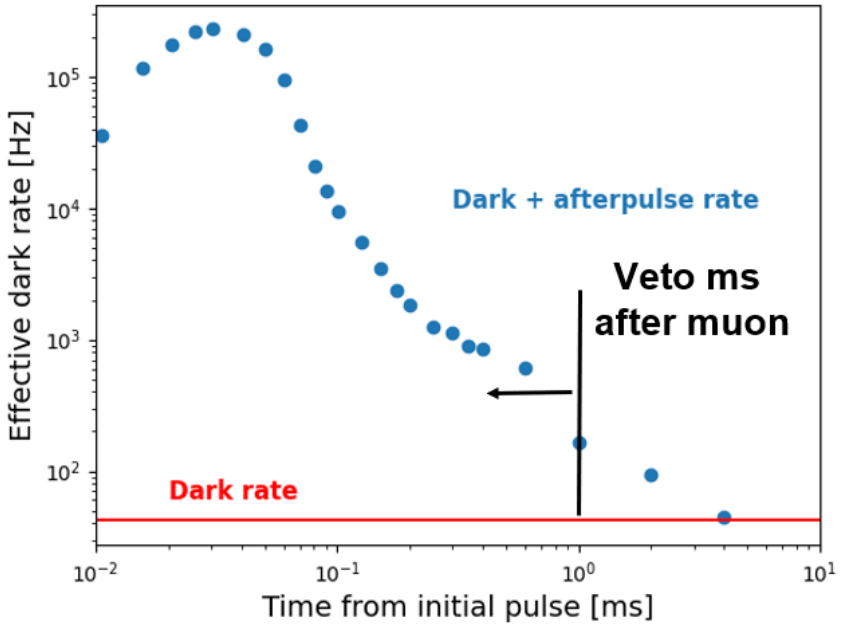


Diagram and plot: Carlos Hernandez Faham

Afterpulsing in the data

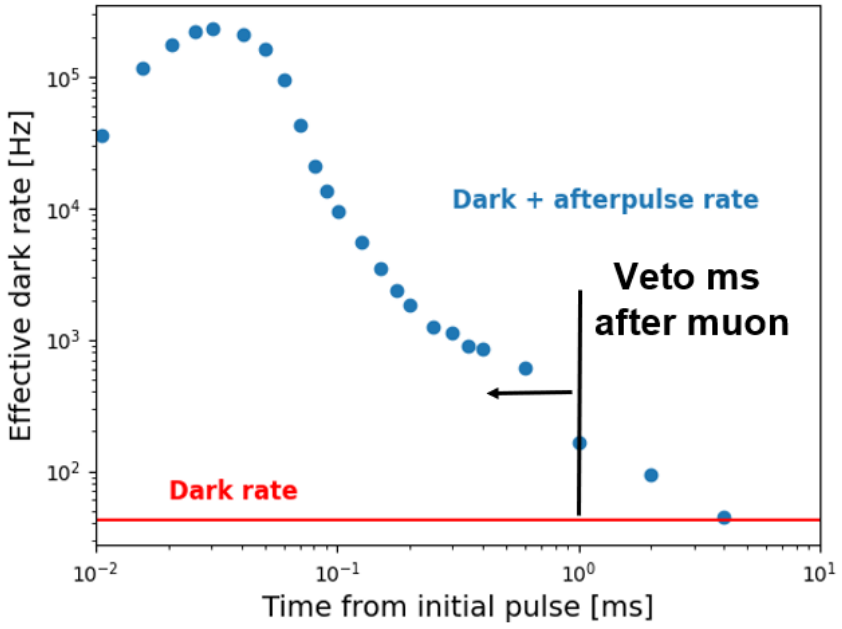
Single PMT Bench Tests (using LED Pulses)



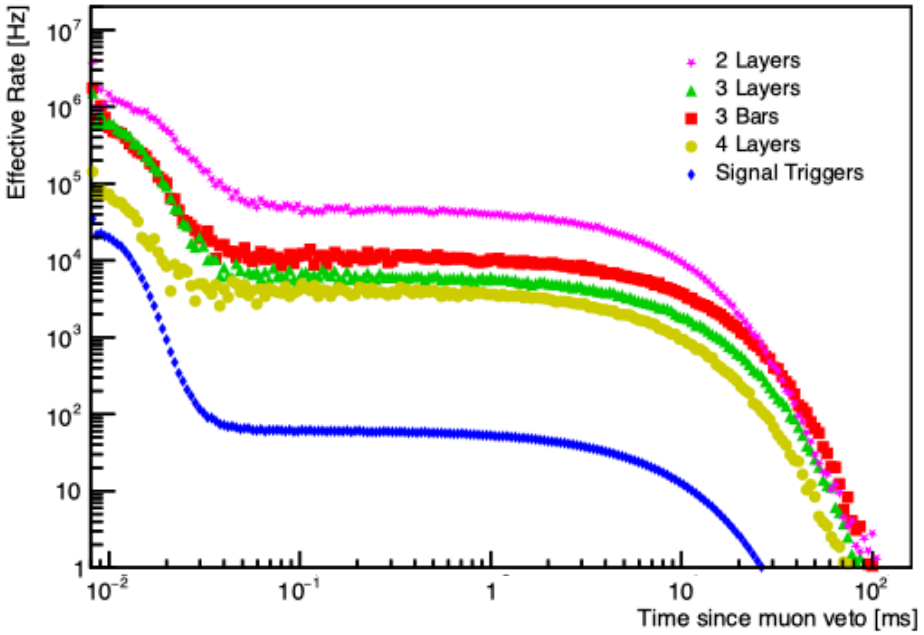
Bench tests indicate a period of ~1ms (muon-like pulse) with enhanced afterpulsing rate

Afterpulsing in the data

Single PMT Bench Tests (using LED Pulses)



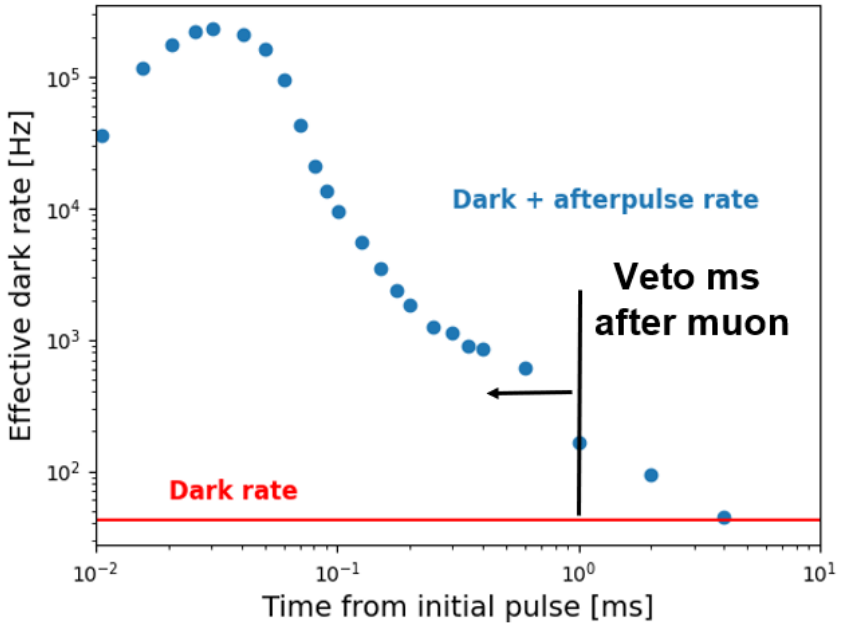
FORMOSA Multi-PMT Coincidence Triggers



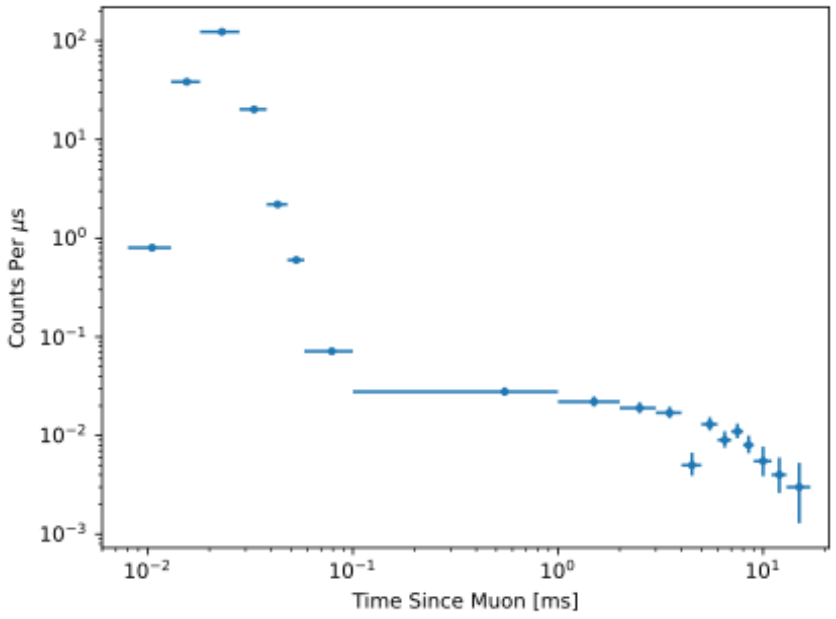
In-situ measurements using FORMOSA triggers show similar behavior to bench tests with LED pulses

Afterpulsing in the data

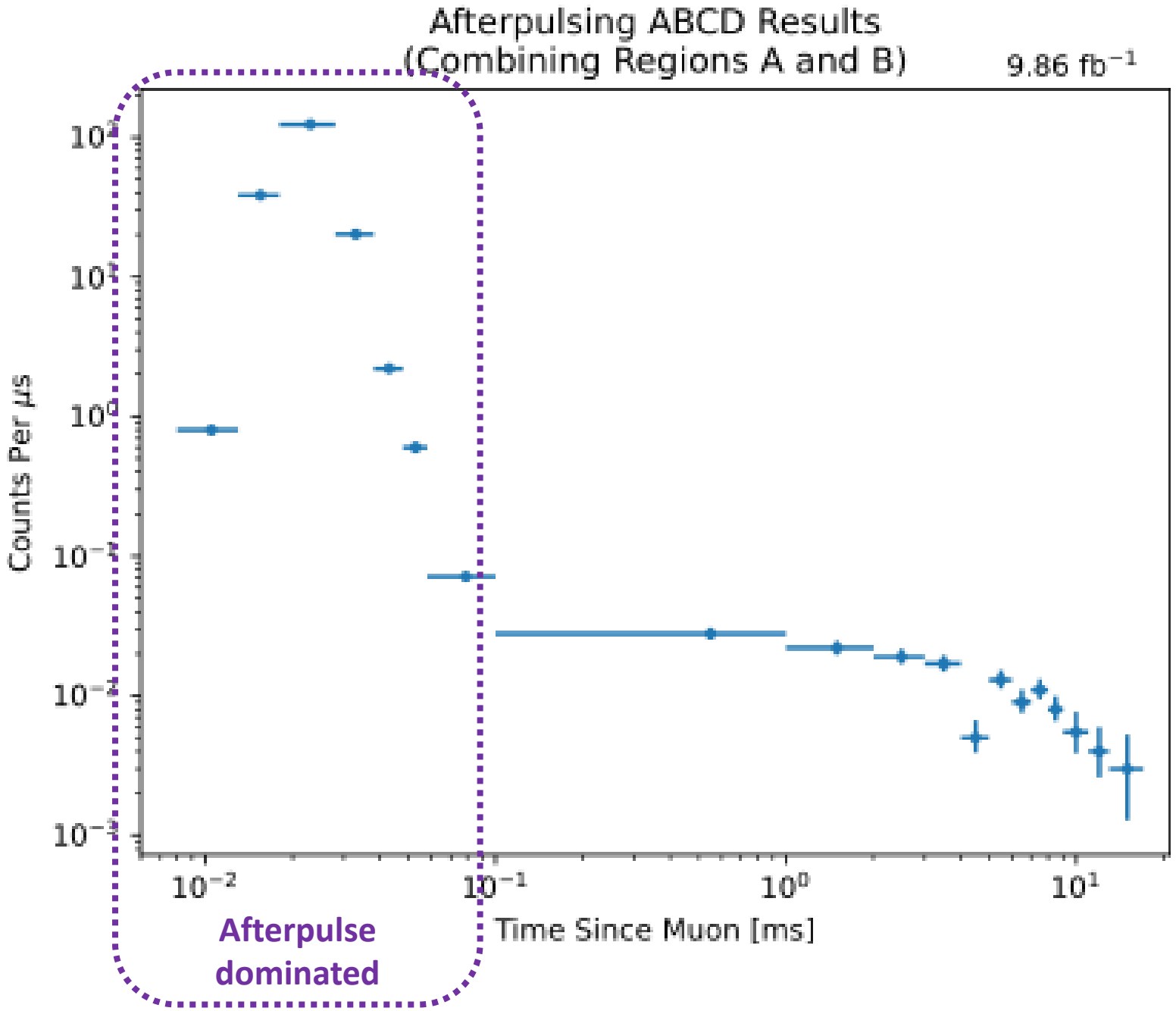
Single PMT Bench Tests (using LED Pulses)

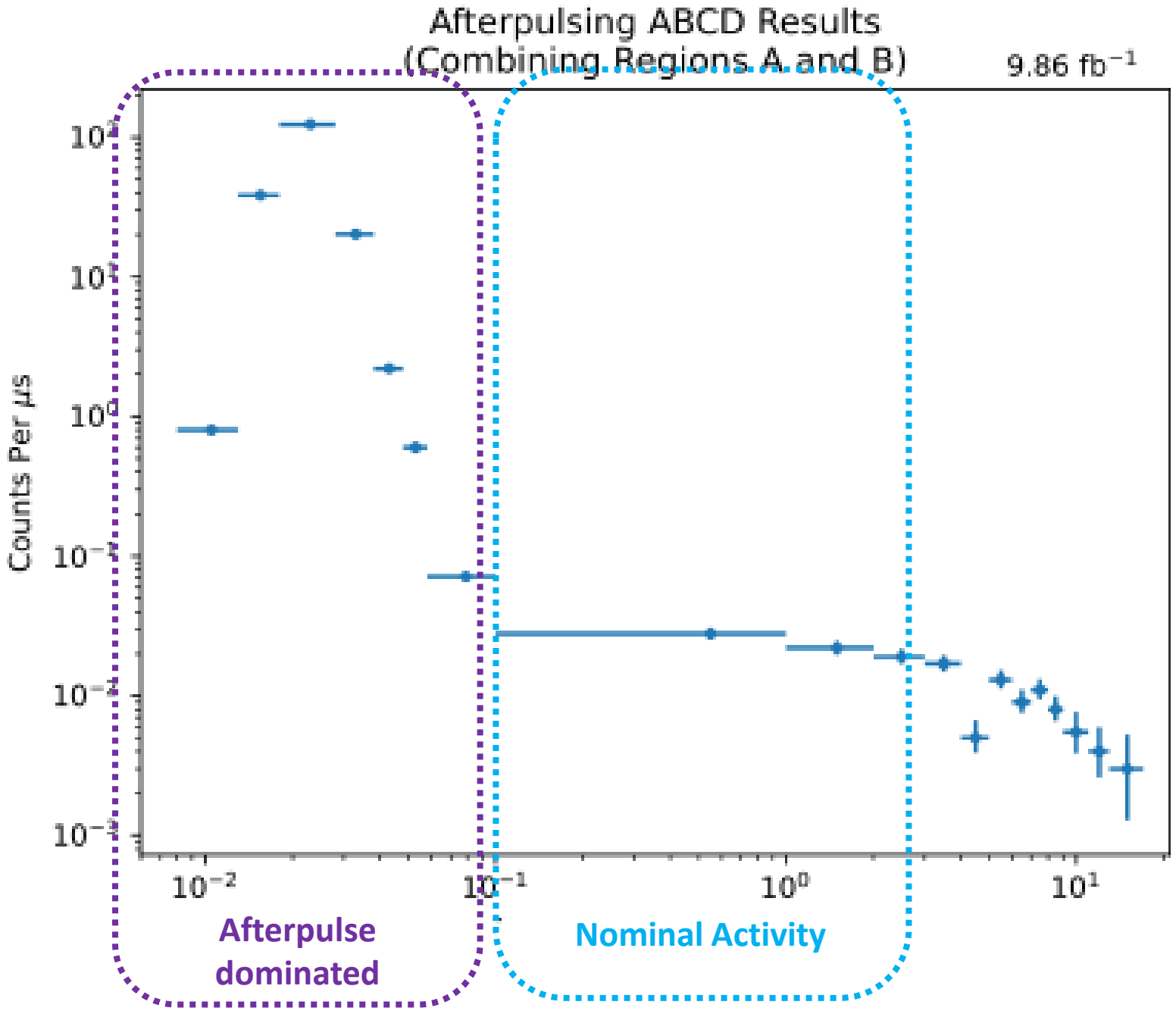


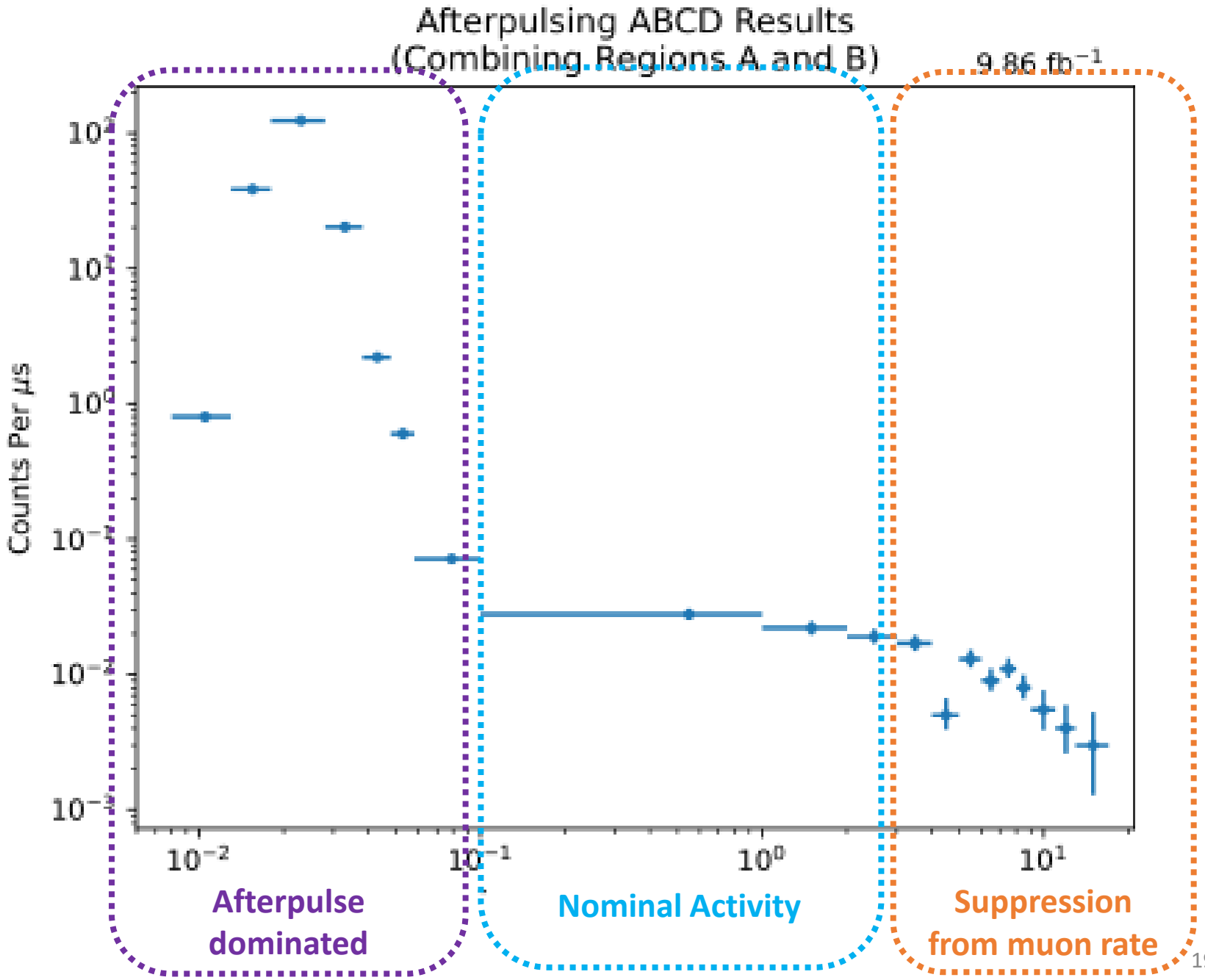
Offline Analysis Using Control Region (Large Δt)

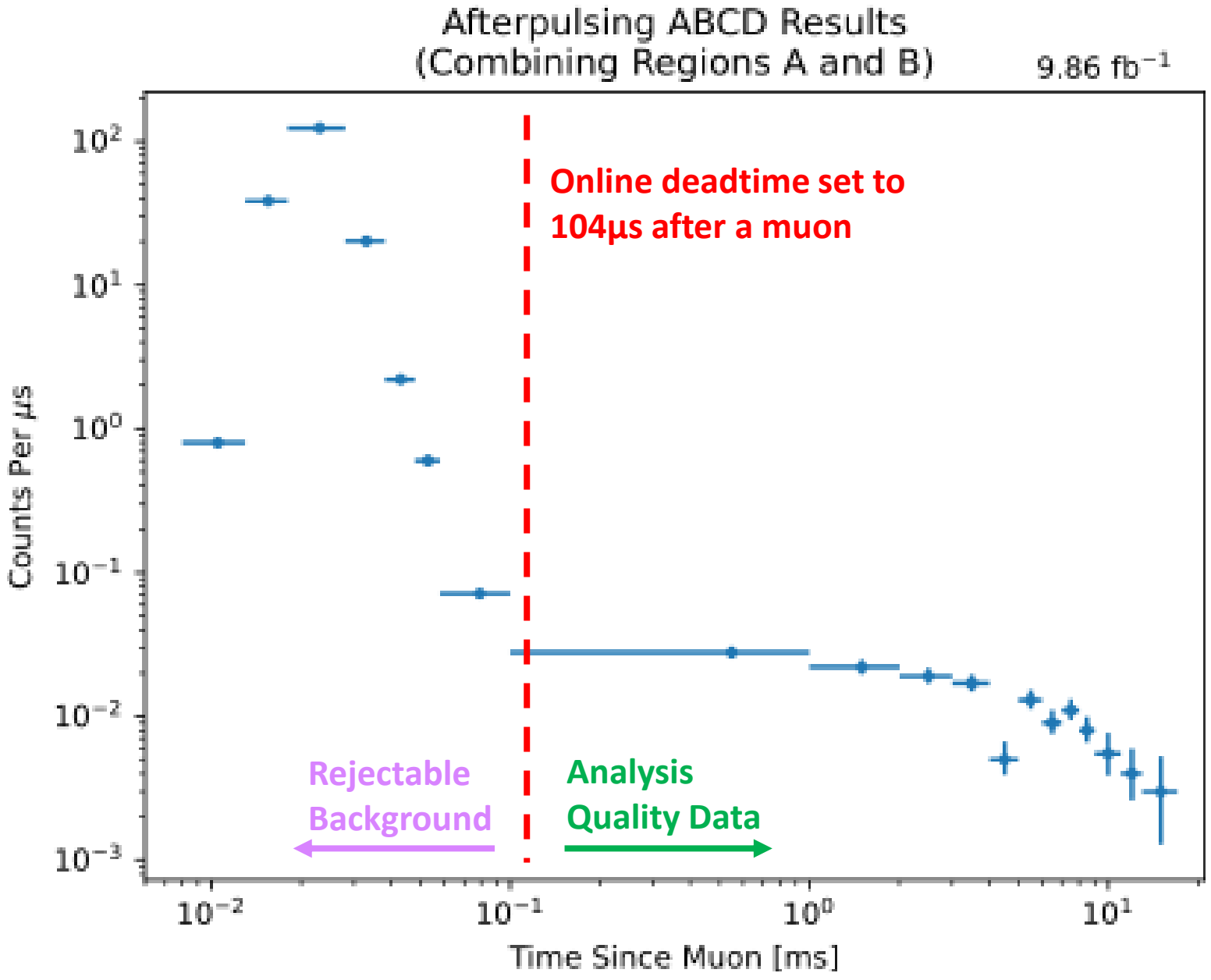


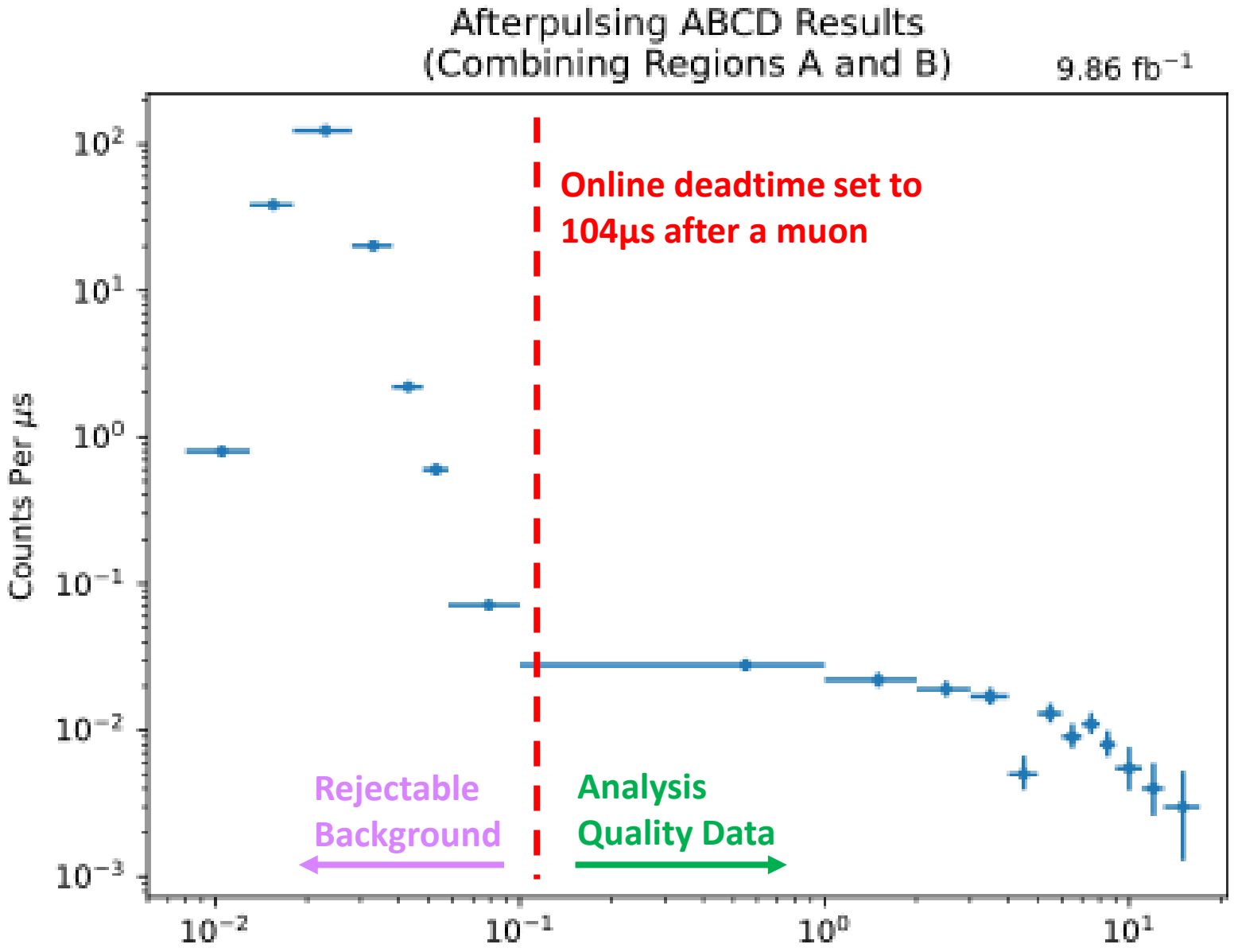
We get a much clearer (and similar) picture when looking at the offline data, selecting control events with a large time difference


Afterpulsing ABCD Results
(Combining Regions A and B)
9.86 fb^{-1}
Counts Per μs
Time Since Muon [ms]
Afterpulse dominated


Afterpulsing ABCD Results
(Combining Regions A and B)
9.86 fb^{-1}
Counts Per μs
10^{2}
10^{1}
10^{0}
10^{-1}
10^{-2}
10^{-3}
10^{-2}
10^{-1}
10^{0}
10^{1}
Afterpulse dominated
Nominal Activity


Afterpulsing ABCD Results
(Combining Regions A and B)
9.86 fb^{-1}
Counts Per μs
10^{2}
10^{1}
10^{0}
10^{-1}
10^{-2}
10^{-3}
10^{-2}
10^{-1}
10^{0}
10^{1}
Afterpulse dominated
Nominal Activity
Suppression from muon rate

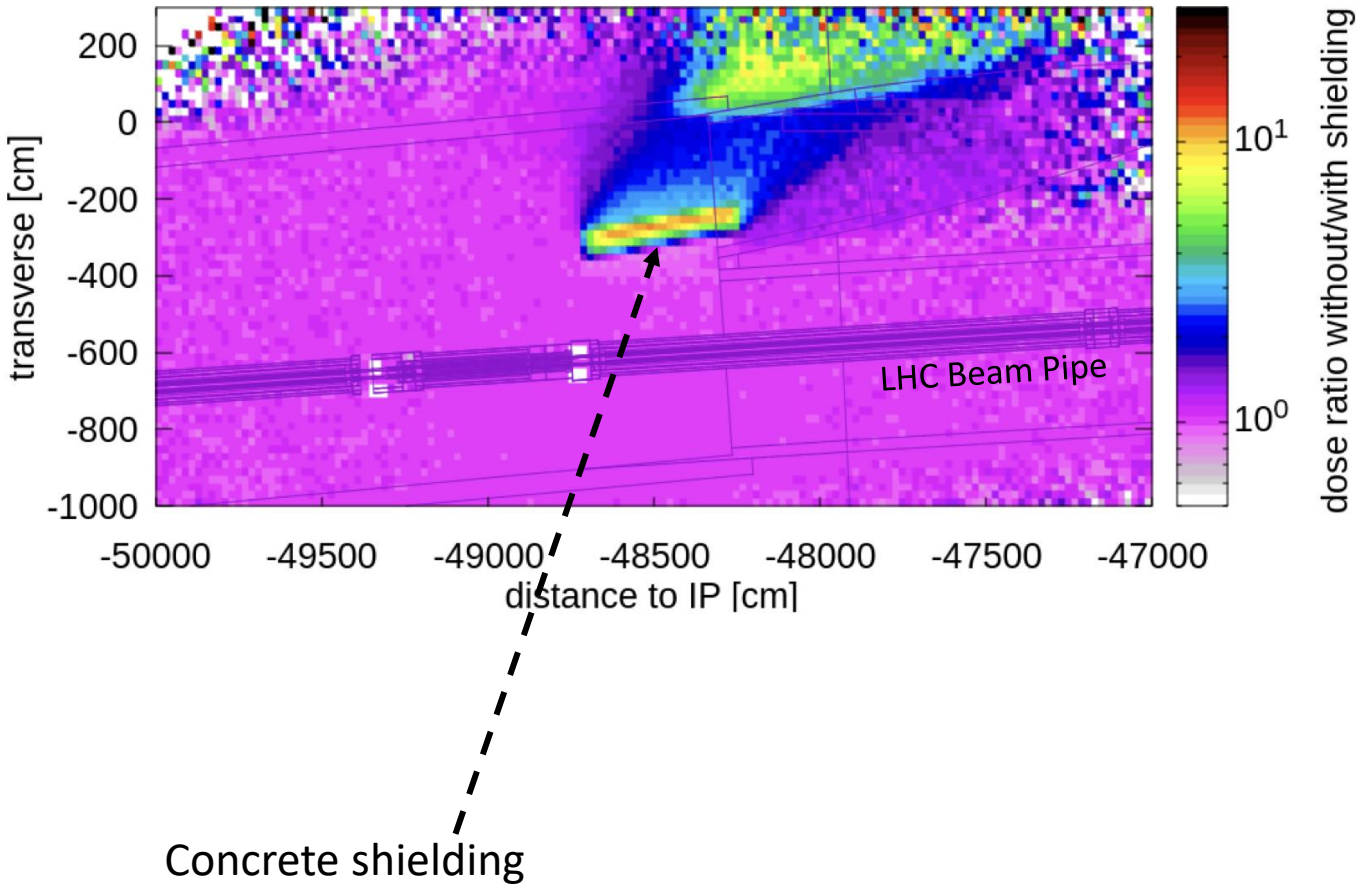

Afterpulsing ABCD Results
(Combining Regions A and B)
9.86 fb^{-1}
Online deadtime set to
104μs after a muon
Rejectable
Background
Analysis
Quality Data
Counts Per μs
Time Since Muon [ms]
10^{2}
10^{1}
10^{0}
10^{-1}
10^{-2}
10^{-3}
10^{-2}
10^{-1}
10^{0}
10^{1}



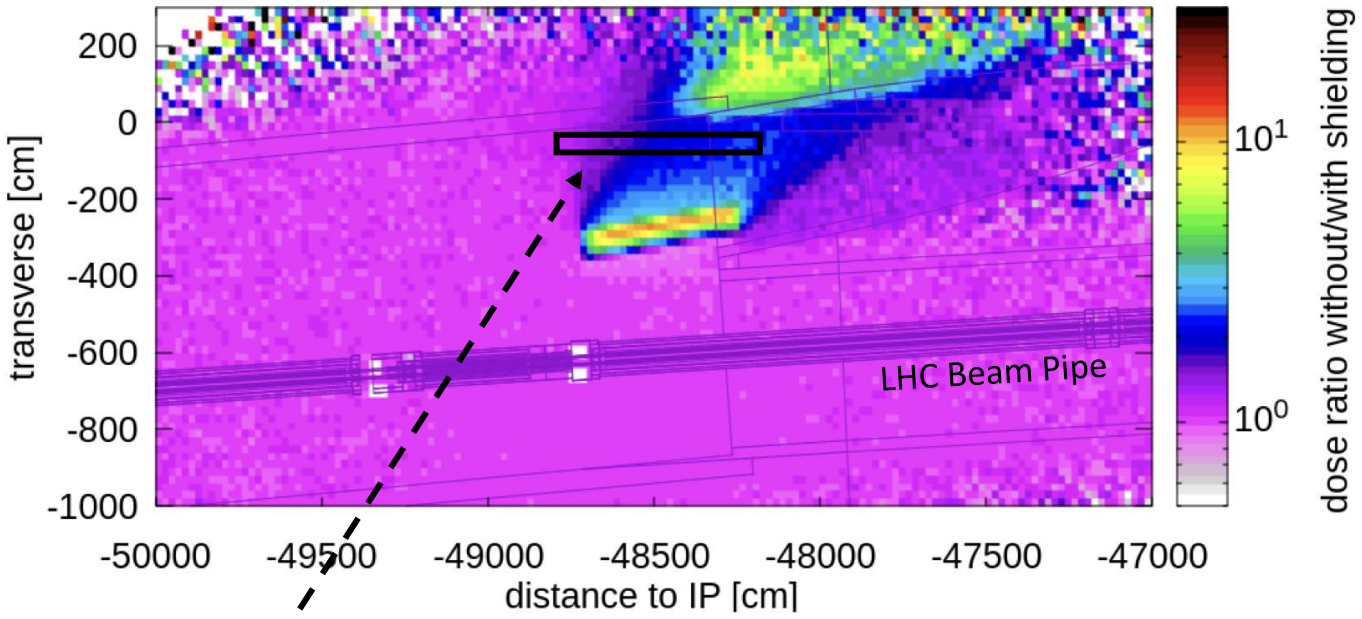
In other words, the demonstrator has done its primary job….

Beam-related background

Beam-related background



Beam-related background

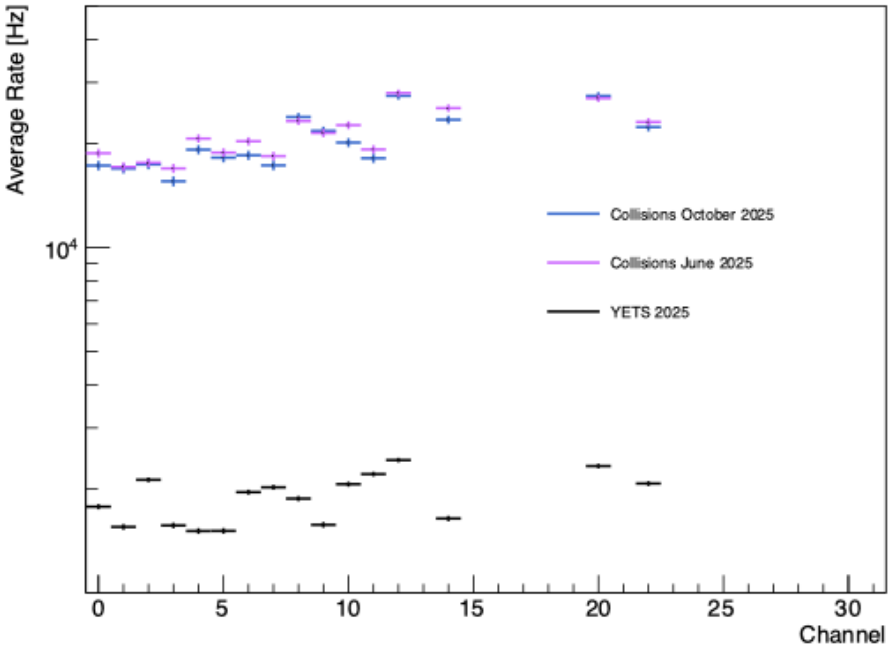


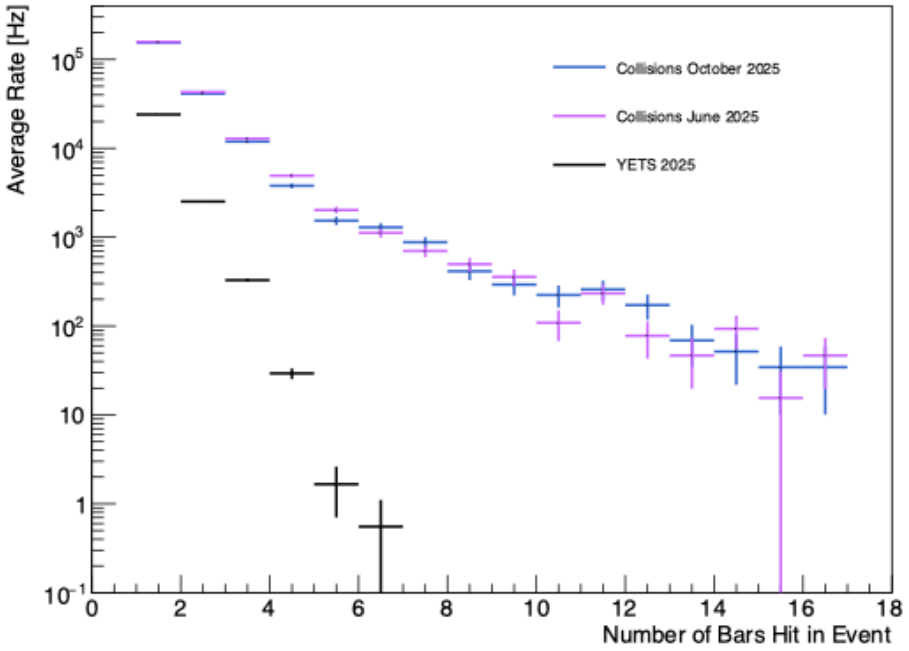
FORMOSA demonstrator

FORMOSA sticks out past the concrete shielding.

Additional panels help us identify radiation-related events

Estimating Background with Zero Bias ….

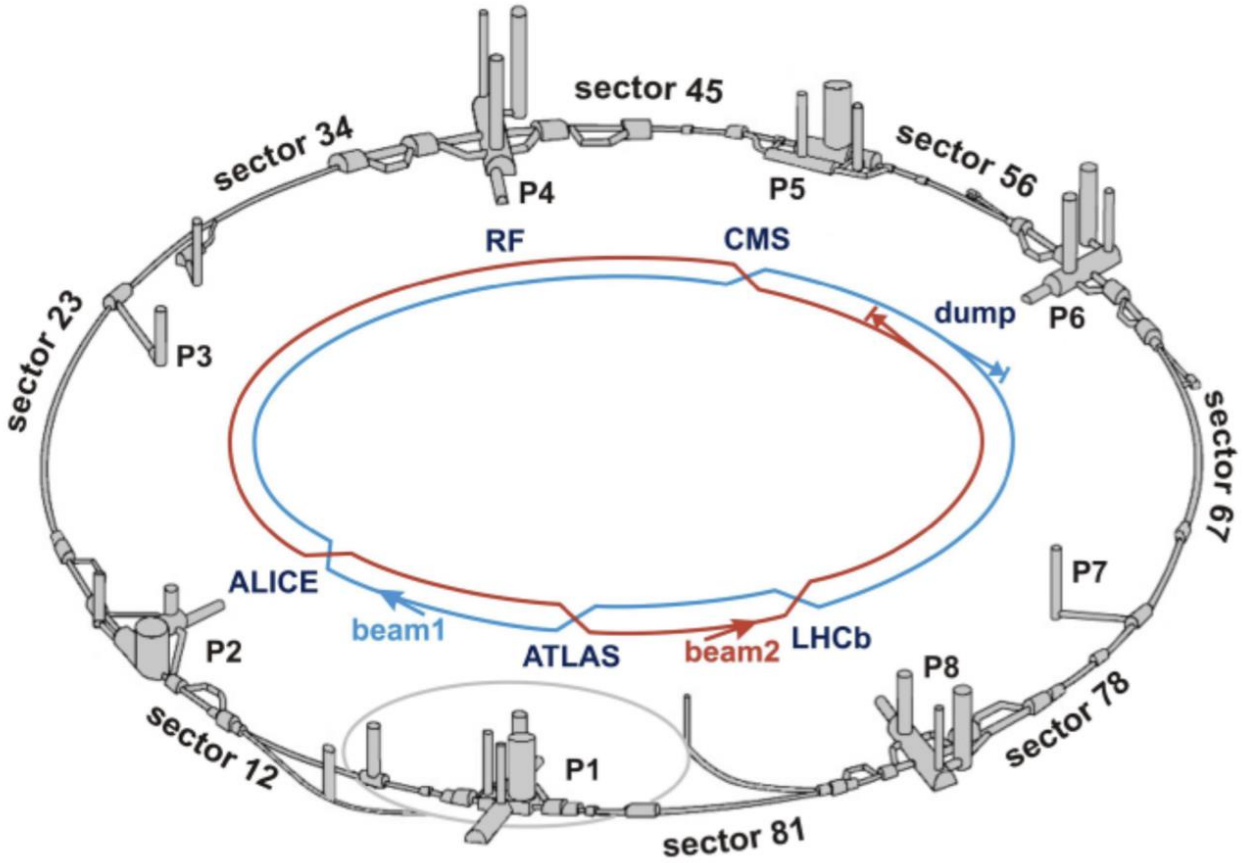




We can compare "dark rates" for beam-on and year-end-technical-stop (YETS) conditions, looking in our consistent 0.5Hz zero bias triggers

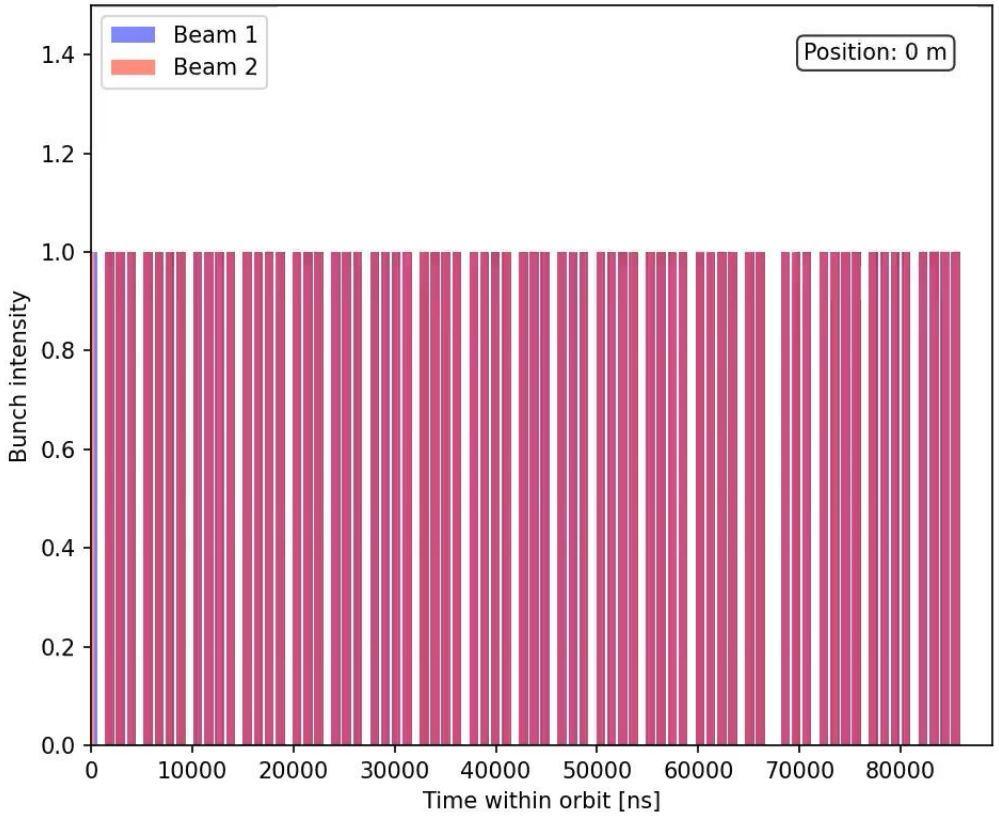
With these rates, we expect a background of O(10) events ☺

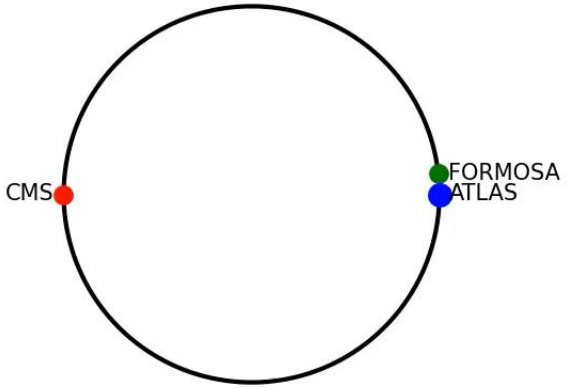
But let's be a little more savvy…



I know the within-orbital time of each event …
can I make sense of our data by building a model?

Let’s build a model based on beam dynamics





We build a model that takes the fill-structure at one position and propagates it to another position along the LHC … follow the **blue** dot!

Time within orbit = Periodic time within fill structure

Building a real model

- Let's target these contributions:
  - Beam 1 radiation
  - Beam 2 radiation
  - Showers muons passing near FORMOSA, but not going through detector volume
  - Uncorrelated backgrounds (dark rate, cosmics, geological radiation…)

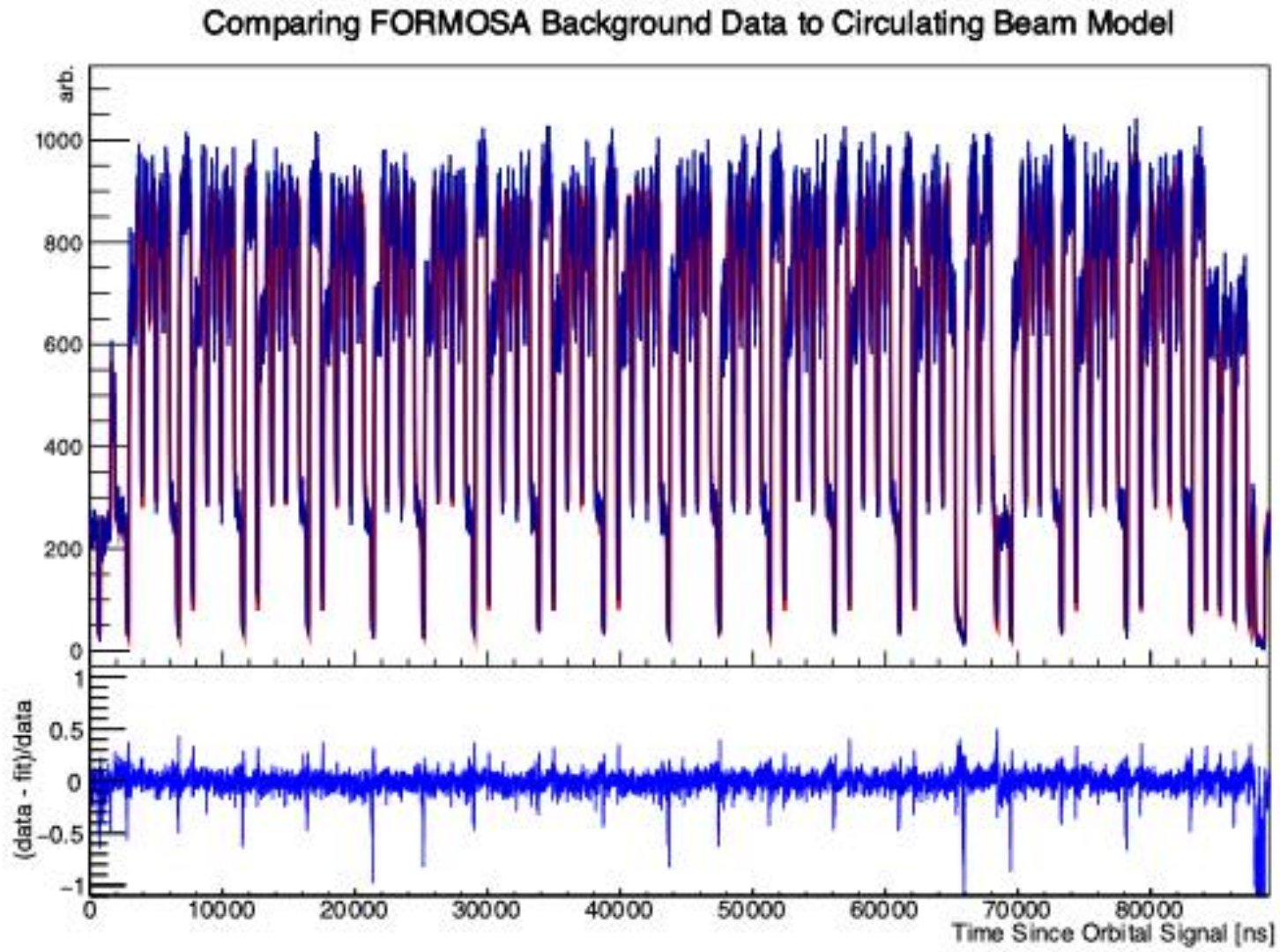
$$f(t) = A_1 * \sum_{i=0}^{Beam1} (I_{1,i} \cdot L(t, \mu_i + a_1, \sigma_1))$$ **Beam 1**

$$+A_2 * \sum_{j=0}^{Beam2} (I_{2,j} \cdot L(t, \mu_j + a_2, \sigma_2))$$ **Beam 2**

$$+A_3 * \sum_{k=0}^{Collisions} ((I_{1,k} \times I_{2,k}) \cdot L(t, \mu_k + a_3, \sigma_3))$$ **Muon Showers**

$$+C$$ **Uncorr. Back.**

The current model

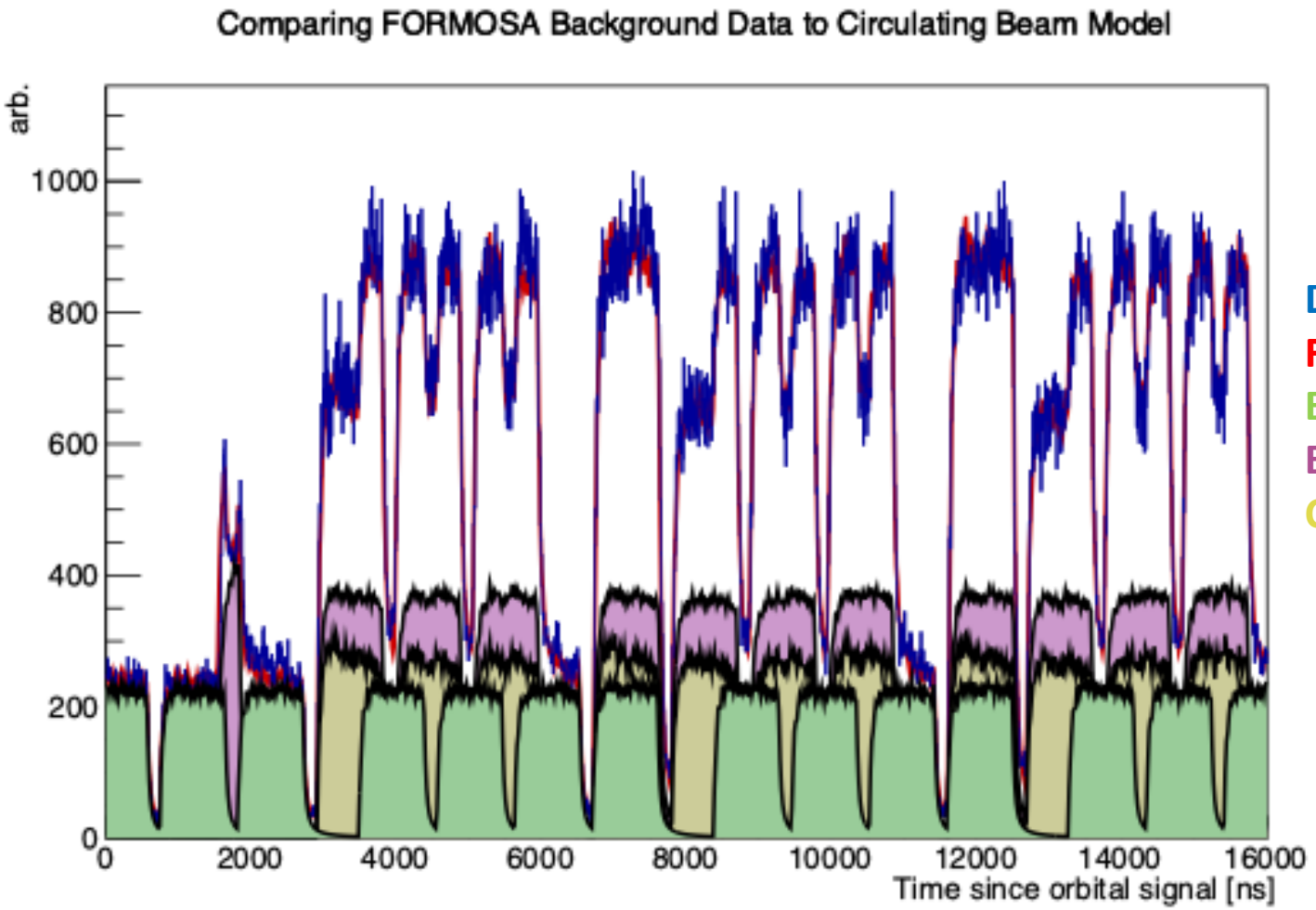


Fit

Data

Time within orbit = Periodic time within fill structure

Zooming-in a bit

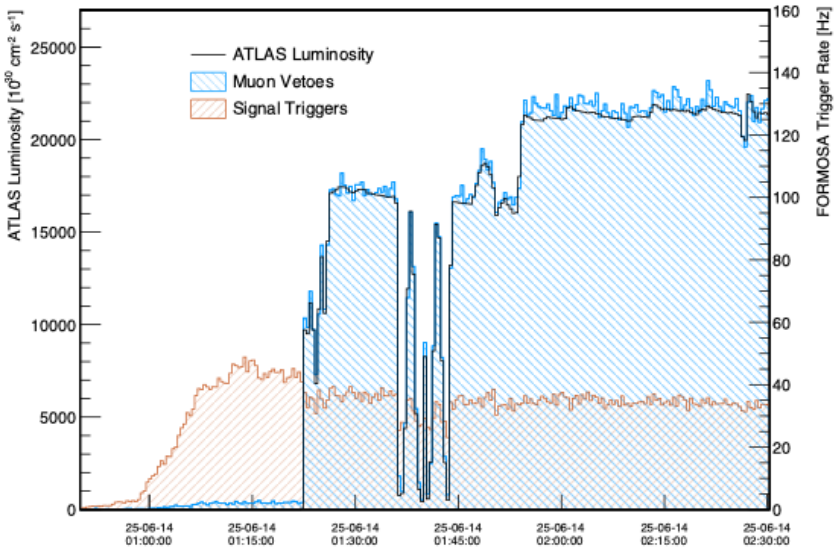


Data
Full Fit
Beam 1 contribution
Beam 2 contribution
Collision contribution

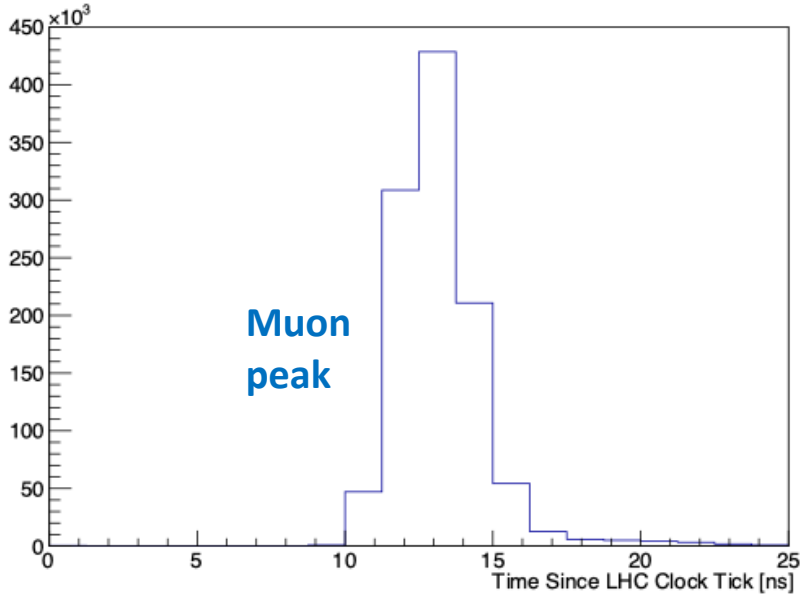
Time within orbit = Periodic time within fill structure

Timing handles

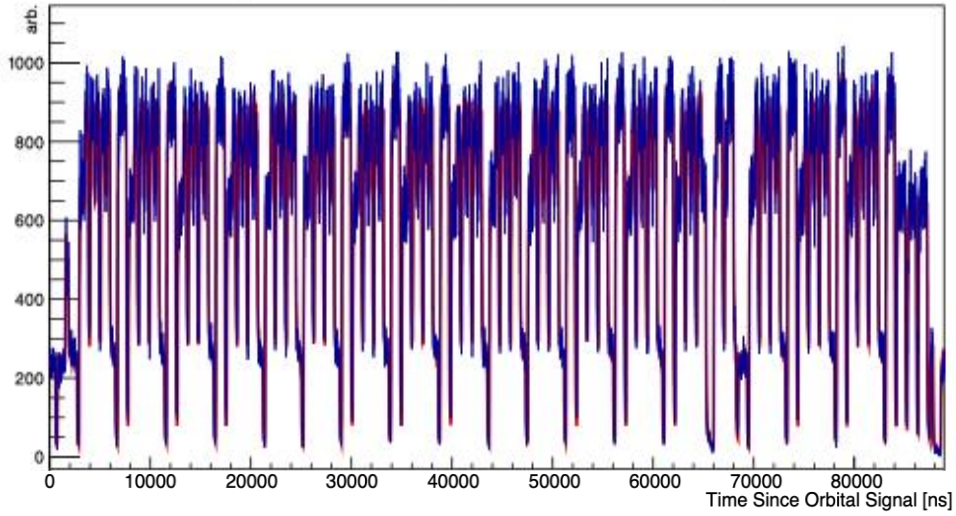
Standard Time



Time within LHC Clock Ticks

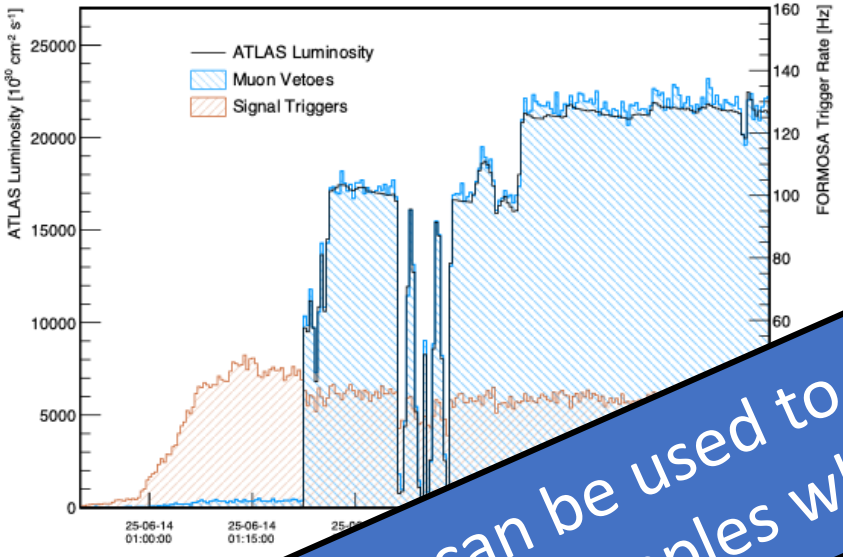


Time within Orbital Period

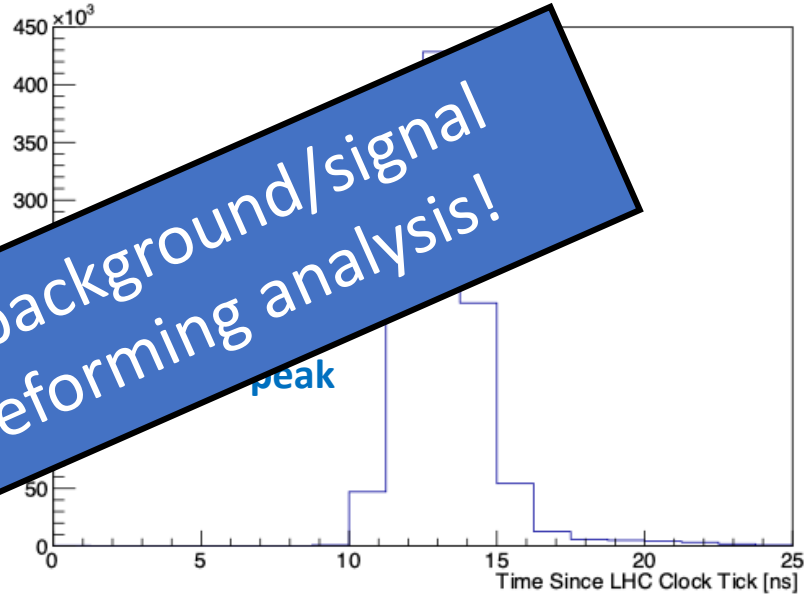


Timing handles

Standard Time

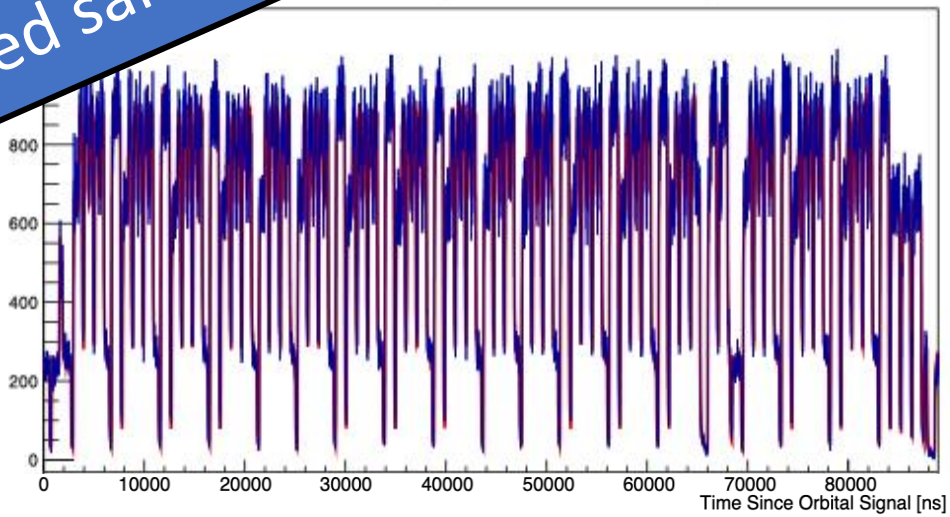


Time within LHC Clock Ticks

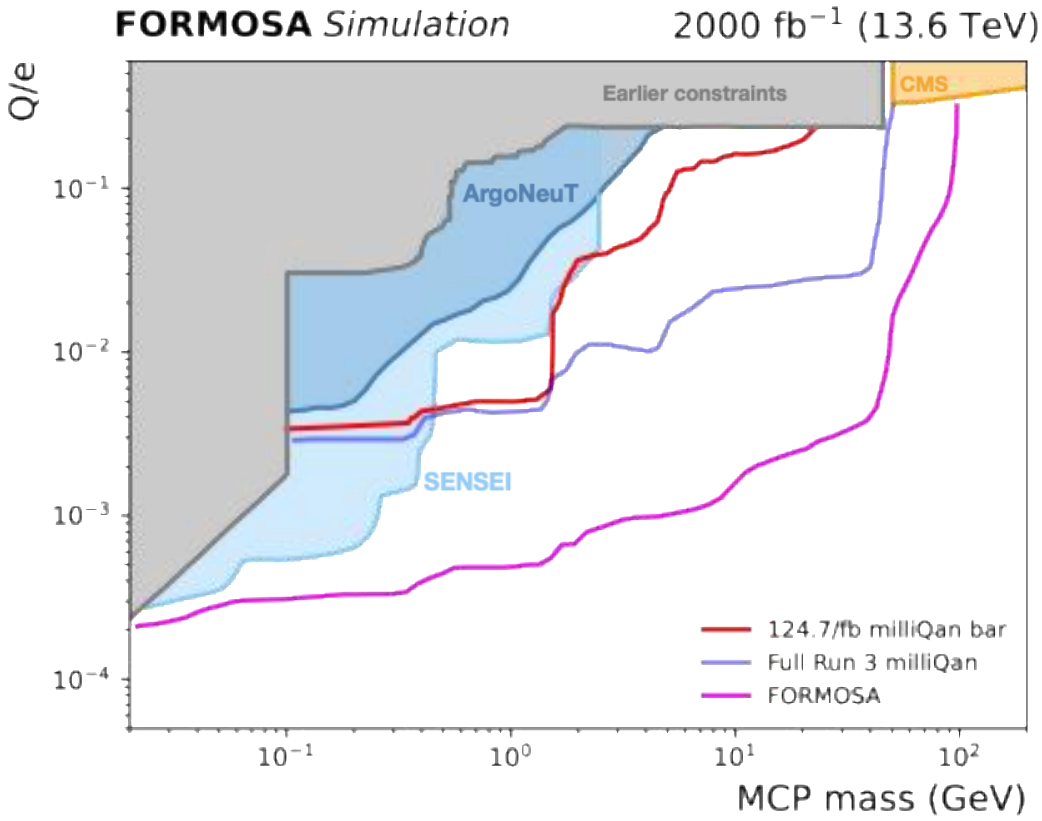


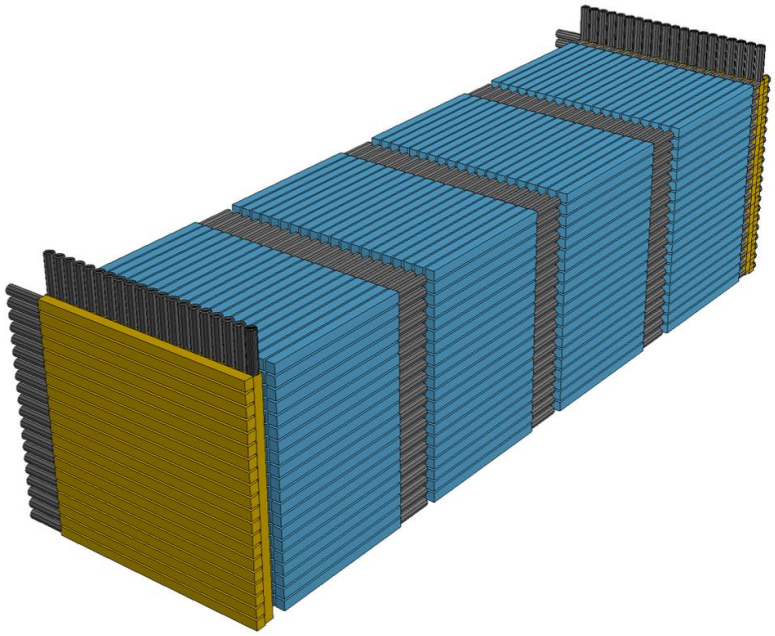
These can be used to have background/signal enriched samples when preforming analysis!

Within Orbital Period



What's the potential sensitivity of such a detector?

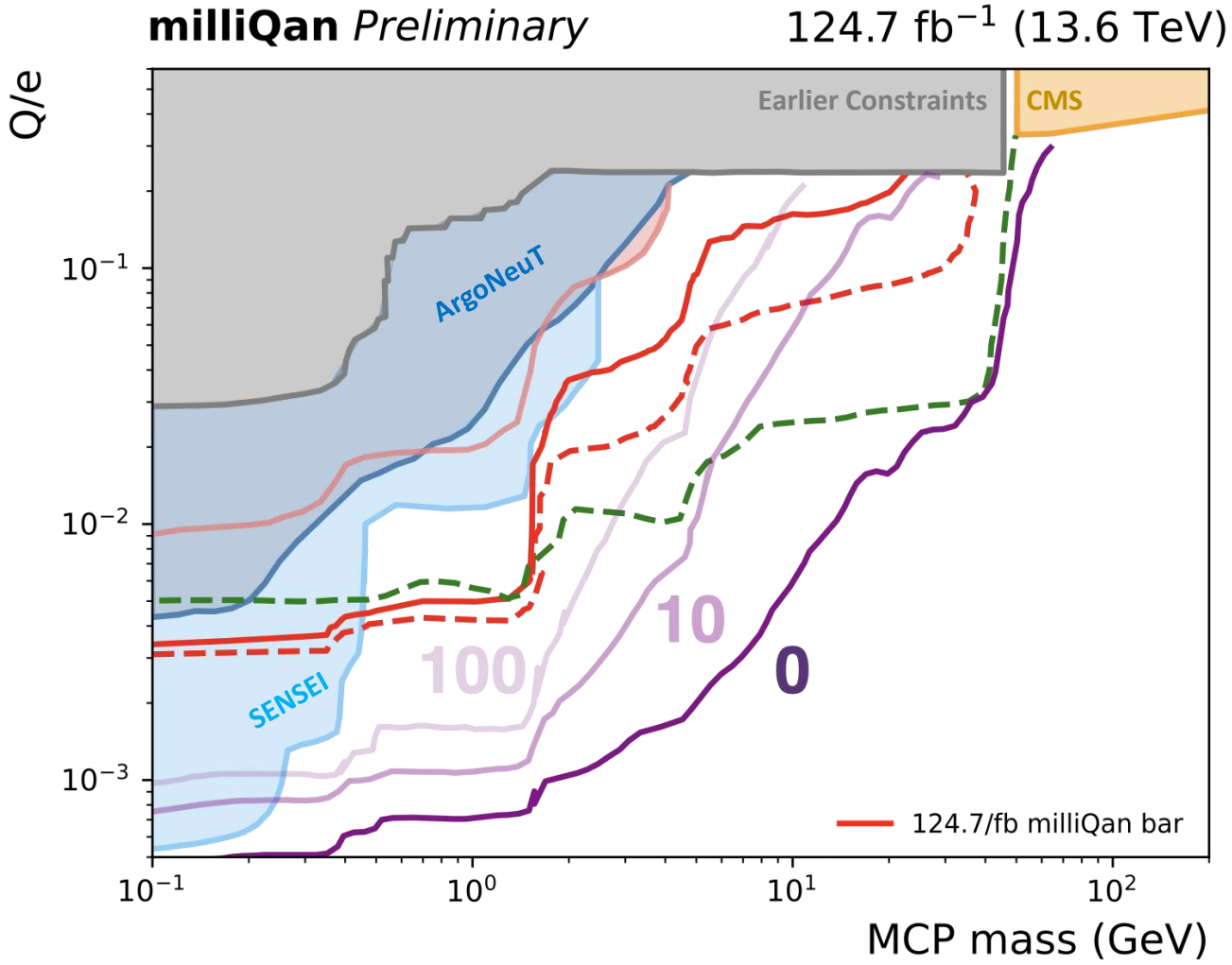




Has the potential for a greatly-advanced sensitivity relative to milliQan

Link to milliQan talk

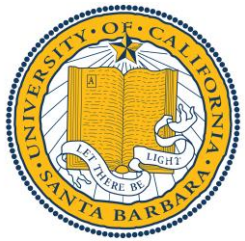
Possible demonstrator sensitivities



Number corresponds to number of background events in this demonstrator analysis

Even in a pessimistic background scenario, world-leading sensitivity is already possible…

Thank you for listening!



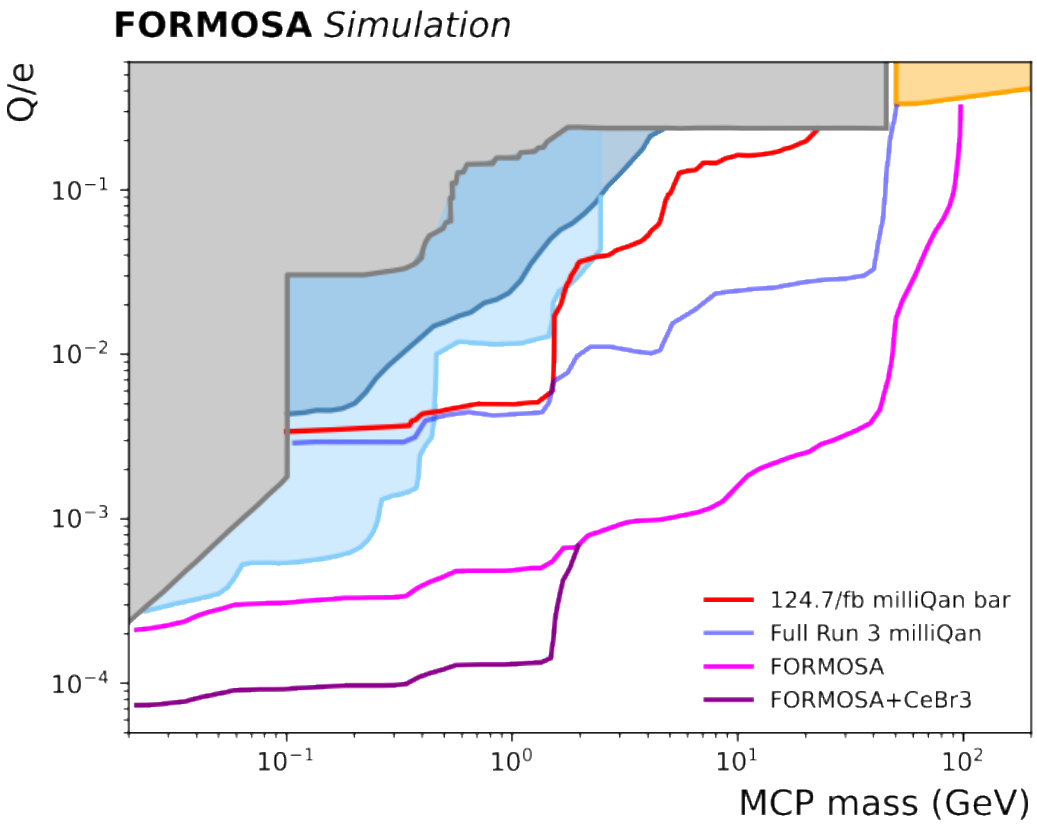
A special thanks to Jamie Boyd, Brian Petersen, Claire Antel, and the **FASER collaboration**. Our work with FORMOSA could not have succeeded without you all!

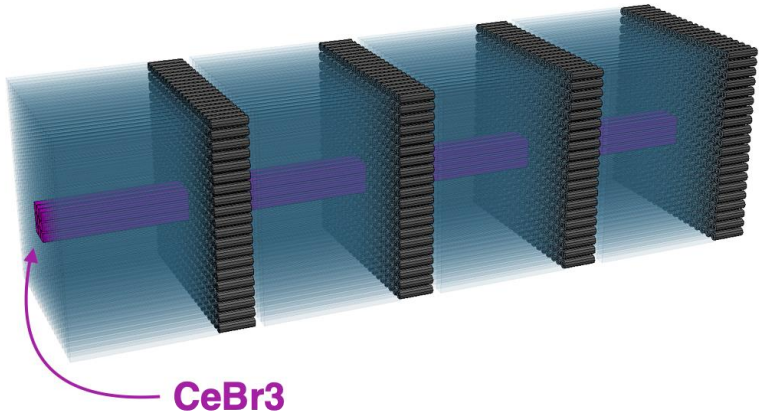
The work of FORMOSA is built on the hard work and success of the **milliQan collaboration**.

This speaker is supported with funding from the **Department of Energy**.

Backup

An alternate design that includes CeBr3





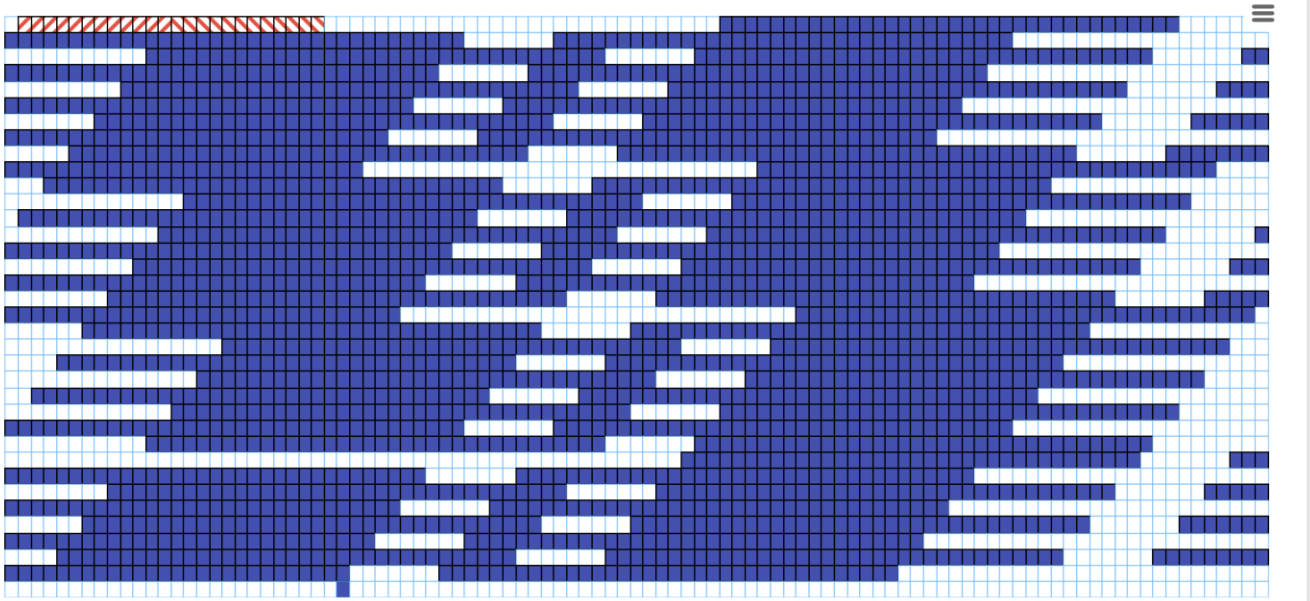
Regions of the detector could be CeBr3

- 35x the light yield of plastic
- 5x the density
- Fast scintillation time constant
- Low intrinsic radioactivity
- More expensive…

Such a material could enhance low-charge sensitivity

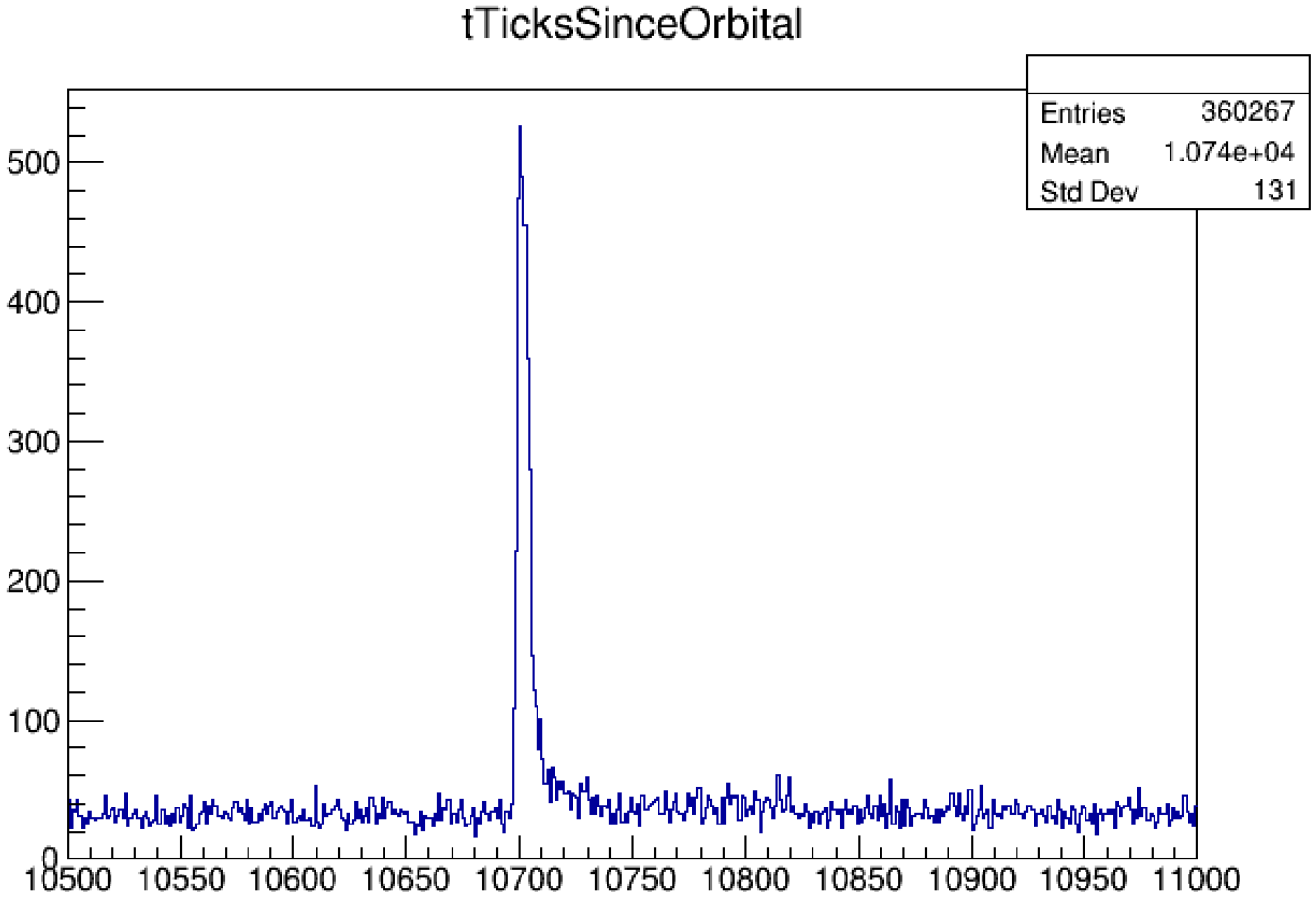
A standard fill structure … 2460b

Bunch Info Chart



Beam 1 > 0.5E10 | Beam 2 > 0.5E10 | Beam 1 and Beam 2 > 0.5E10 | Beam 1 > 1E10
Beam 2 > 1E10 | Beam 1 and Beam 2 > 1E10 | Luminosity detected | Configured for beam
Not configured for beam

Fill Details

Fill	10666
Stable Duration	16:19:16
Start Time UTC	2025-05-25 10:07:52
Stable Beams Start UTC	2025-05-25 12:19:33
End Time UTC	2025-05-26 04:40:02
Delivered Lumi	995.773 pb^{-1}
Recorded Lumi	940.909 pb^{-1}
Efficiency By Time	97.31 %
Efficiency By Lumi	94.49 %
Init Lumi	9.118 $10^{33} cm^{-2} s^{-1}$
Peak Lumi	21.997 $10^{33} cm^{-2} s^{-1}$
Peak Spec Lumi	0.004 $10^{33} cm^{-2} s^{-1} (10^{11} p)^{-2}$
Peak Pileup	63.923
Fill Type	PROTONS
Filling Scheme	25ns_2460b_2448_2089_2227_1
Crossing Angle	0 μrad
β*	120 cm
Energy	6799.0 GeV

Why might a Landau work well for the beam model?