FORMOSA

looking forward to millicharged particles at the LHC

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on behalf of the FORMOSA Collaboration

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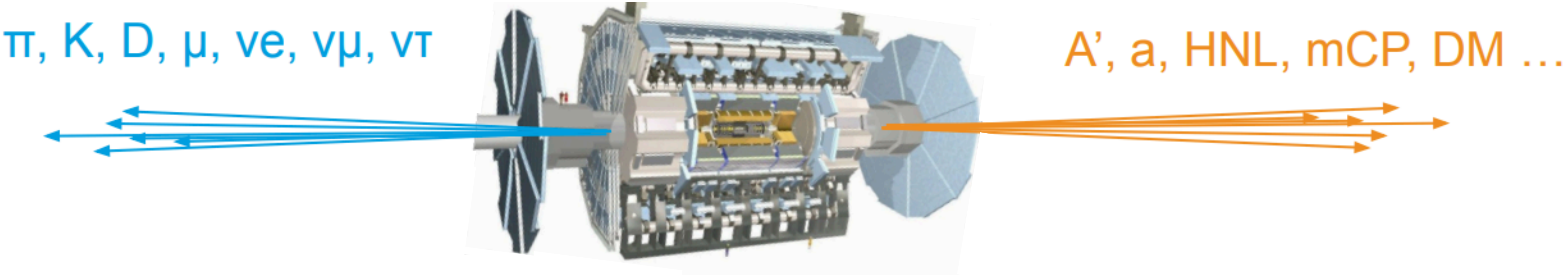
Searching for new physics

- New physics searches limited by the design of existing general-purpose experiments
- Take advantage of already-happening LHC collisions
  → forward region of e.g. ATLAS I.P. very rich in SM and potential new physics



- Physics collisions already happening → no considerable additional operational cost
  → Initial investment needed for the construction of the facility in the forward region
  → Allows for design and installation of dedicated detectors

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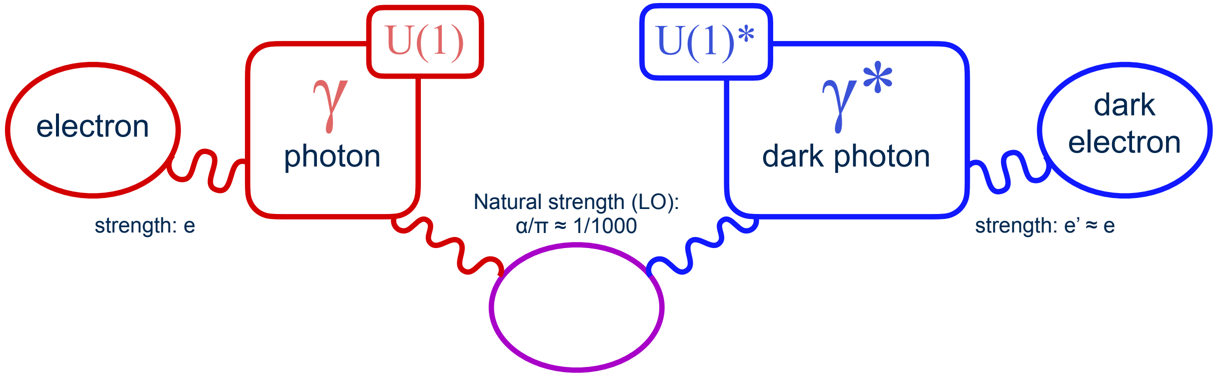
New physics and dark matter → Hidden Valley

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

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

New physics and dark matter → Hidden Valley



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

→

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

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

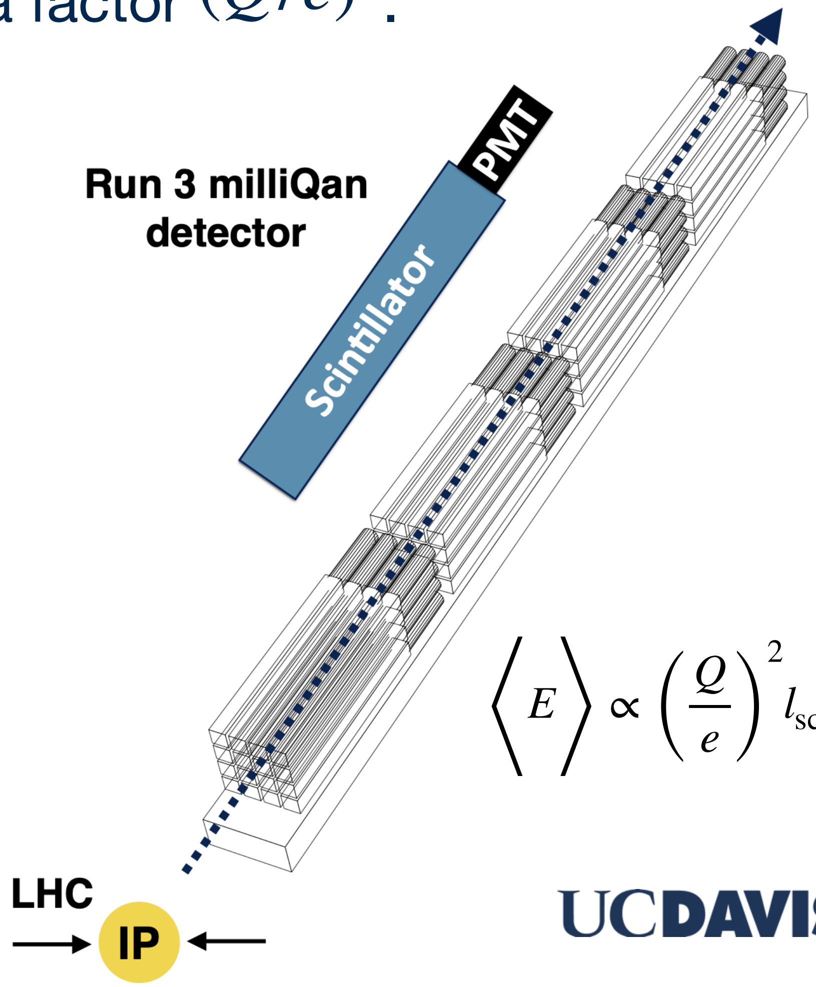
Millicharged particle searches at the LHC

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.

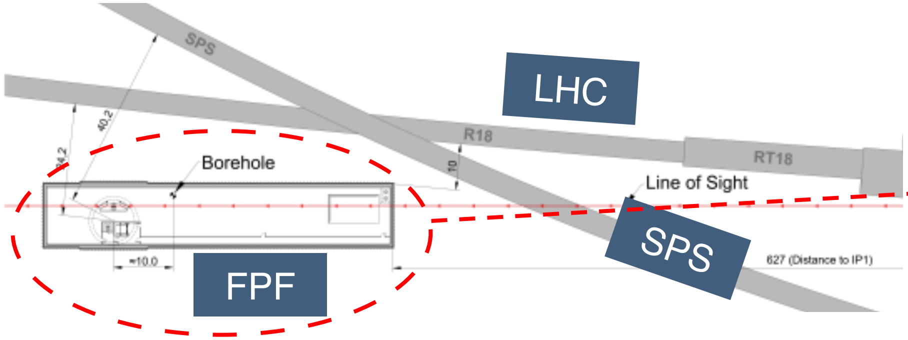
Challenges:

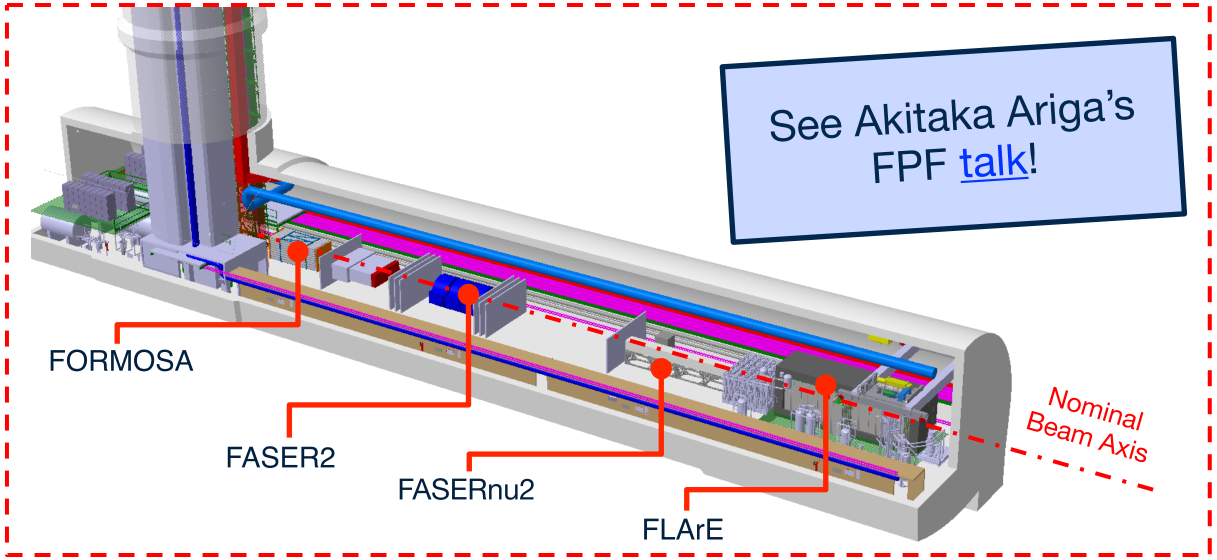
- Expect few scintillation photons to be produced
  → must be able to detect single scintillation photons
- Well controlled backgrounds → signatures "point" at the interaction point, triggering on sets of signals within small time windows (~15 ns)



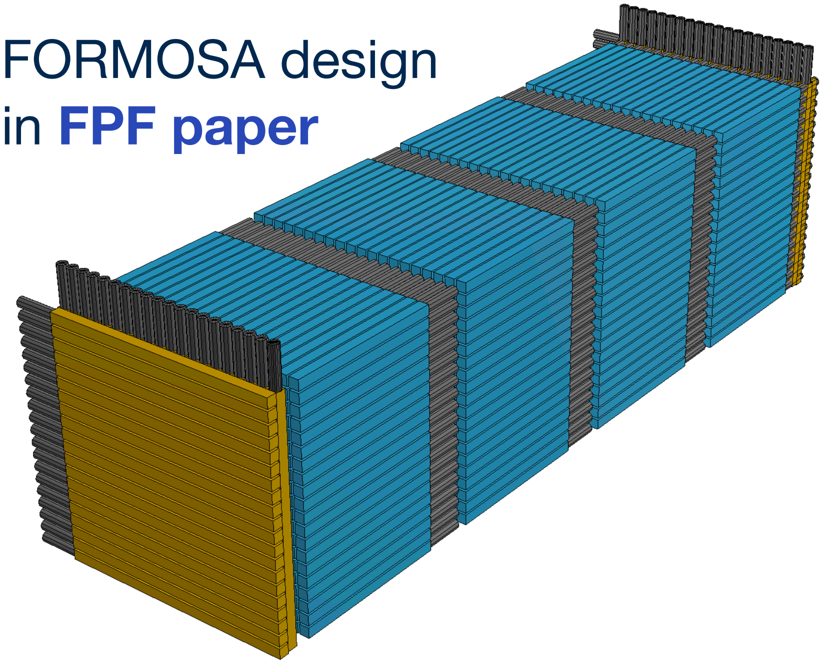
$$\left\langle E \right\rangle \propto \left(\frac{Q}{e}\right)^2 l_{\text{scint}}$$

FORMOSA at the FPF





FORMOSA design in **FPF paper**



Aimed at the ATLAS I.P., located in the very-forward region ($\eta > 9$)

Expect to see **~250x rate** of millicharged particle detection in the forward region compared to the central one (i.e. milliQan, $\eta \sim 0$)

20 rows x 20 cols x 4 layers of bars for detection

Shielded from most SM particles produced at the I.P. by ~ **200m of rock**
Shielded from LHC beam radiation by **>10m of rock**
Main background: collision muons → segmented muon veto panels

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Main background at FPF: I.P. muons

Muon background/radiation flux simulated and validated (CERN FLUKA team)

- expected muon flux $O(1\ \mathrm{Hz/cm^2})$ within 1m of LOS
- affected by triplet magnets
- studing if flux can be reduced with sweeper magnet

Important to understand DAQ strategy to take into account muon-induced activity

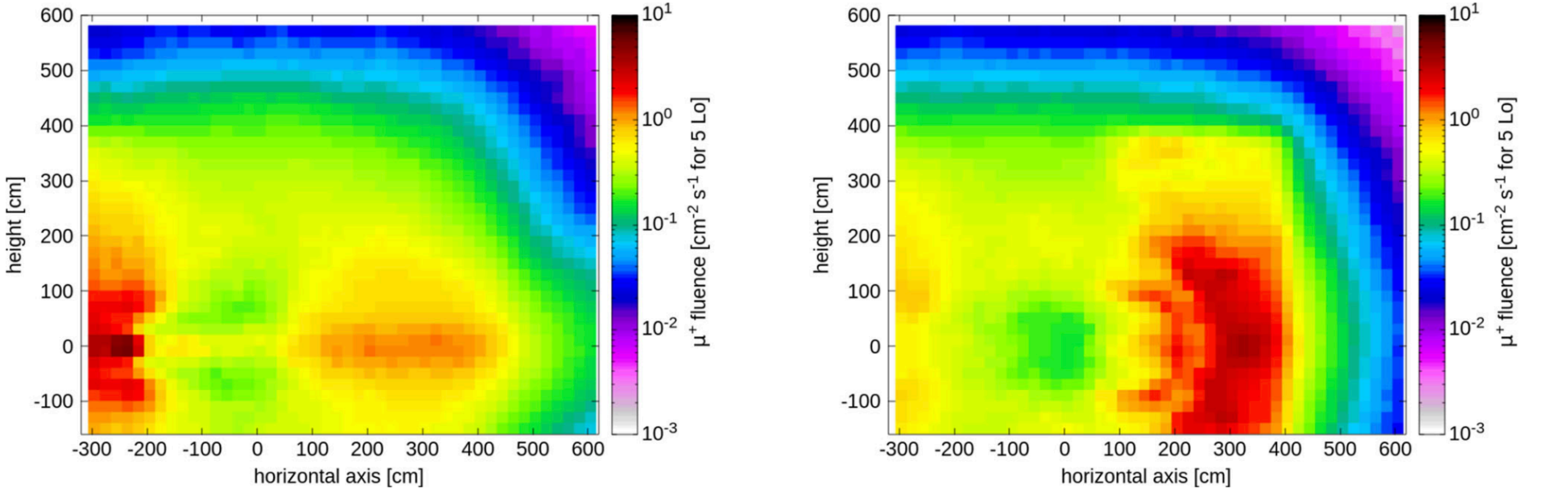

Fig. 14 The muon fluence rate for μ^- (left) and μ^+ (right) in the transverse plane in the FPF cavern for the HL-LHC baseline luminosity of 5×10^{34} cm^{-2} s^{-1}. The coordinate system is defined such that (0, 0) is the LOS, and -ve x is towards the center of the LHC ring

See FPF's input to **ESPPU** for more details

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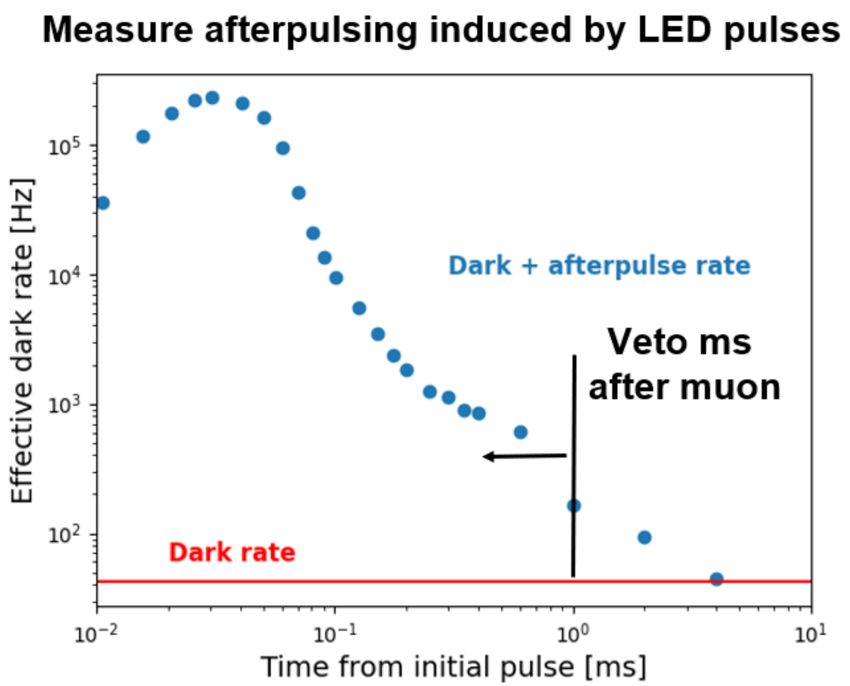
Main background at FPF: I.P. muons

Muon background/radiation flux simulated and validated (CERN FLUKA team)

- expected m … o understand DAQ
- affected by … take into account
- studing if flu … nduced activity

Large induced signals (such as those left by muons) can lead to a temporary "increase" of the PMT's dark rate, making triggering unreliable.

Lab bench studies suggest we can work around it by applying a small cooldown deadtime.



height [cm]

μ+ fluence [cm-2 s-1 for 5 Lo]

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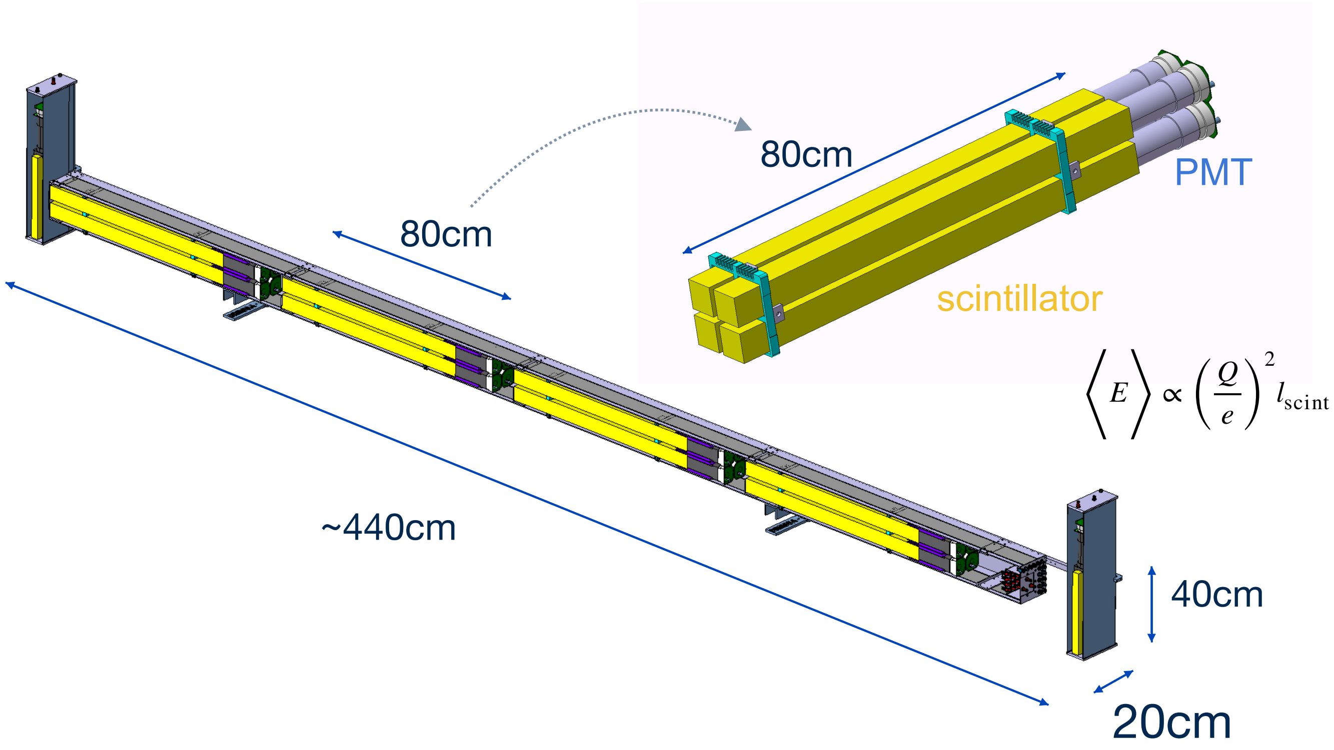
See FPF's input to ESPPU for more details

The FORMOSA demonstrator

A small-scale version of the full FORMOSA was installed during YETS2023-2024 to **prove concept** and **target new phase space**

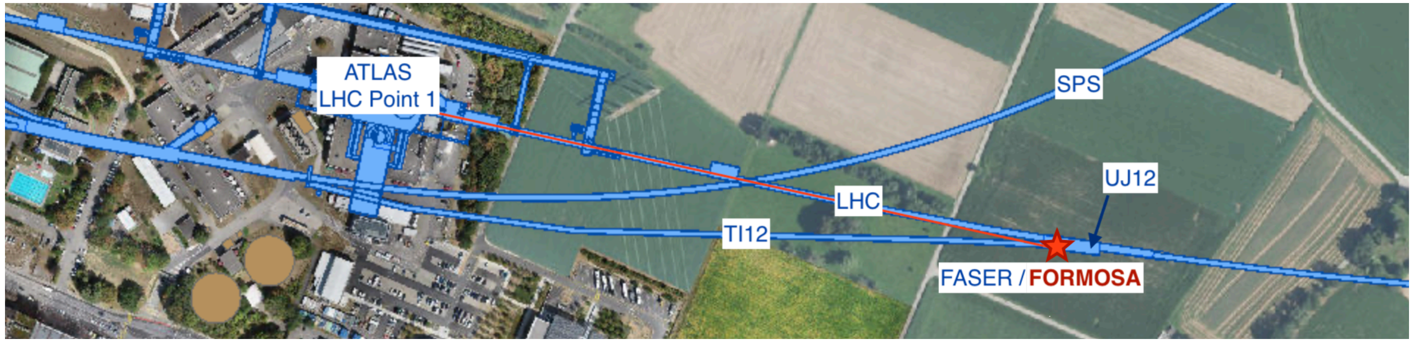
- 2 rows x 2 columns x 4 layers of bars
- front+back muon veto panels



Located in the UJ12 cavern (behind FASER), in the opposite side of the to-be FPF

Additional features added later:

- CeBr3 test module
- Hermetic side+top panels

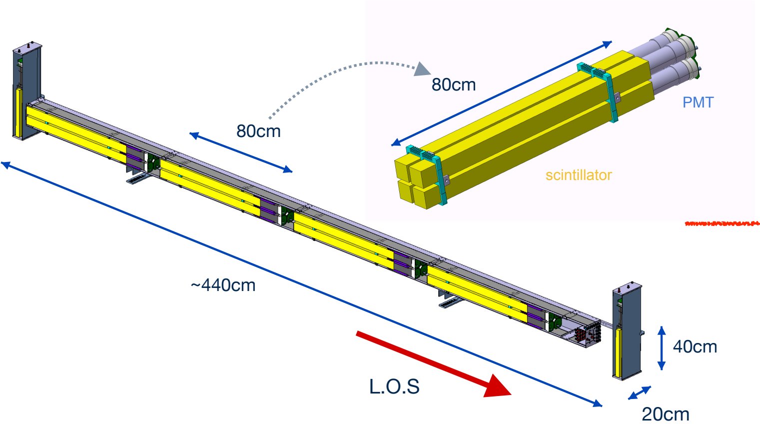


The FORMOSA demonstrator

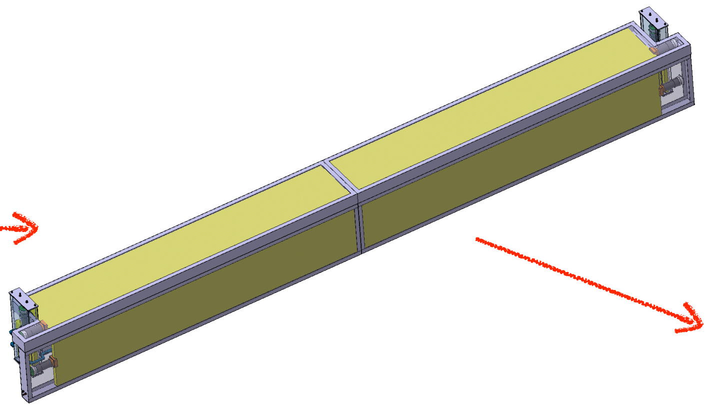
Proof of concept: collecting data and validating design/DAQs through Run 3

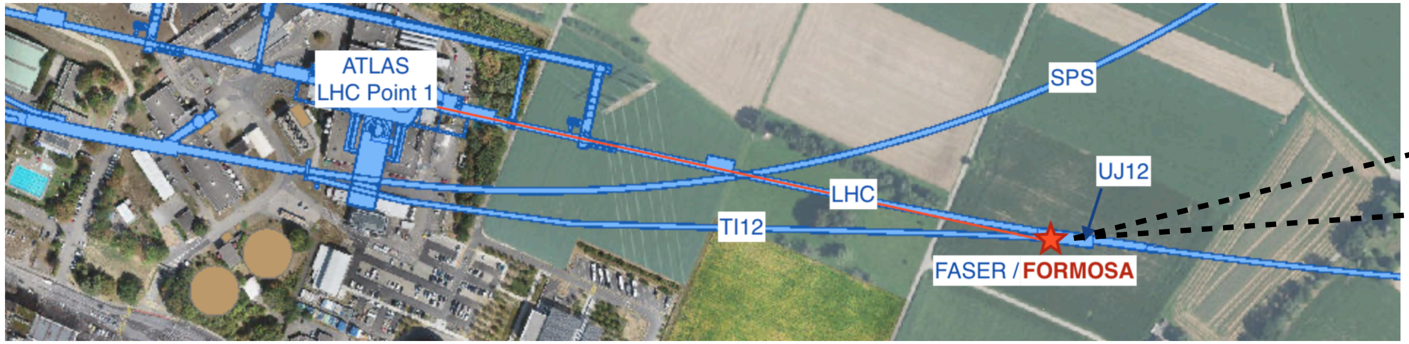
Design evolving to test new technologies and adapt to UJ12's environment

2024



2025





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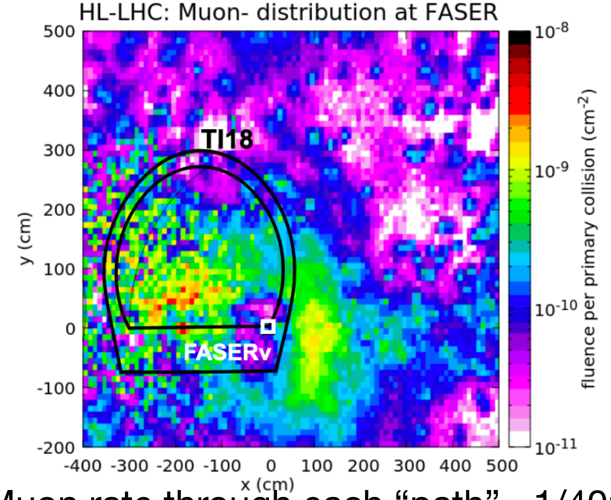
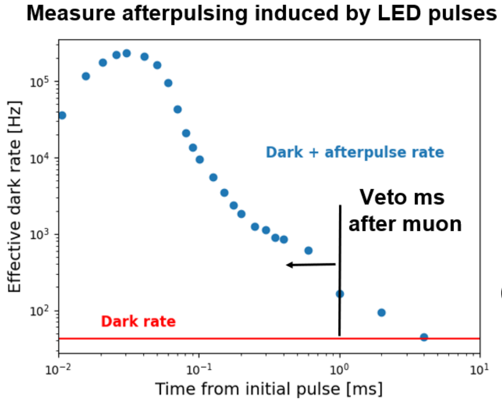
Main backgrounds at the demonstrator

Dominant expected background in the forward region:

afterpulses initiated by through-going muons



Muon rate through each "path" ~1/40ms



Lab study:
Can devote a ms of deadtime to cool down following a collision muon. But muons are frequent (~100Hz for demonstrator), so can't wait too long

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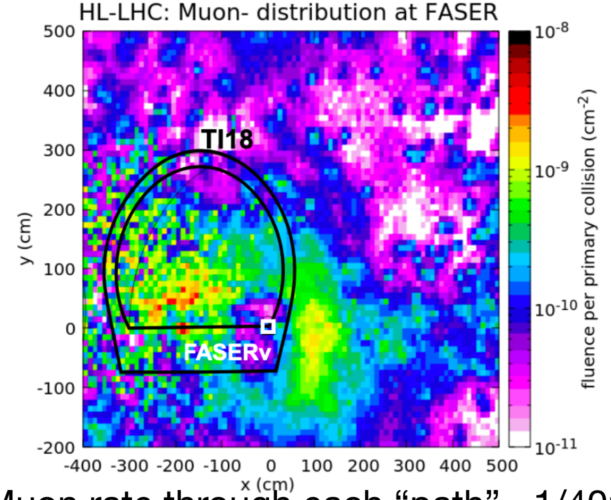

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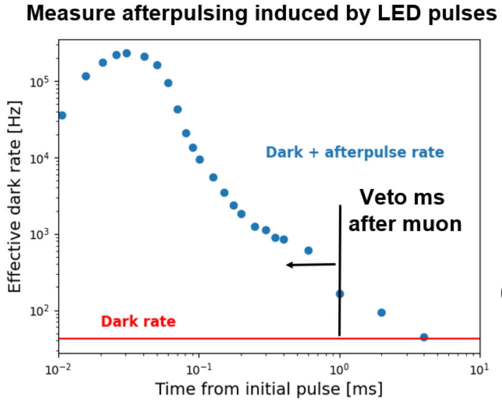

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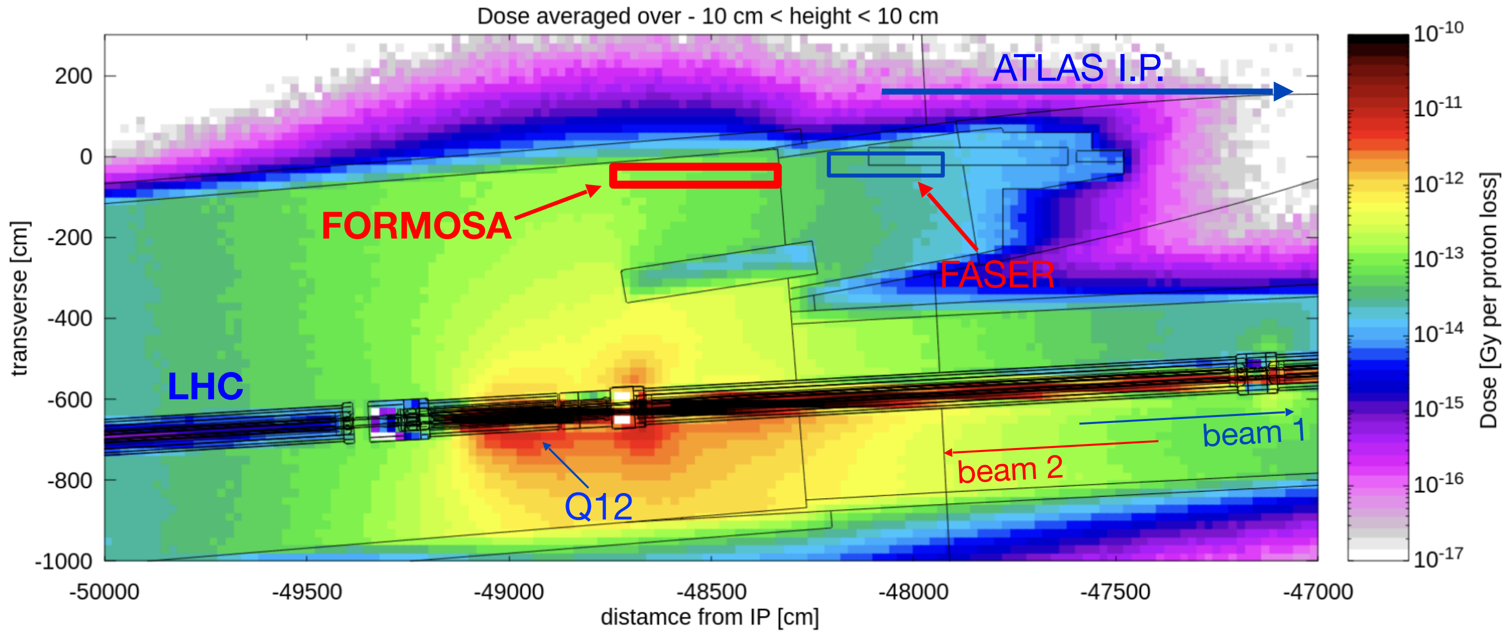
An additional challenge at demonstrator: **Q12 beam background**

(N.B. this background will NOT be present in the FPF)



Absolute average dose due to proton loses at Q12 (simulation provided by FASER)

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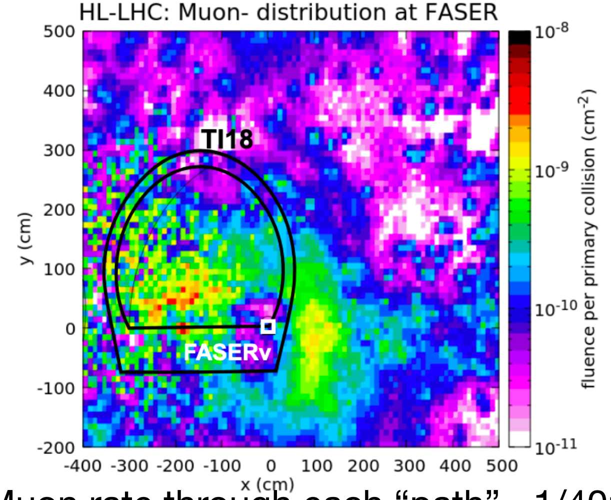

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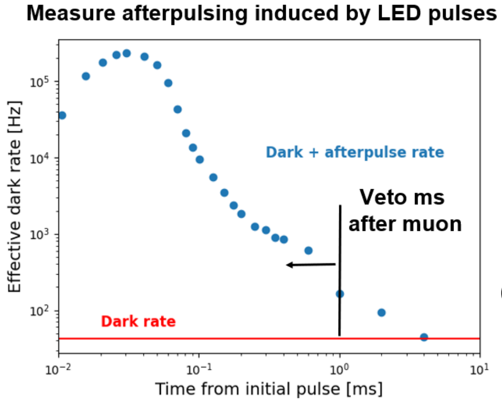

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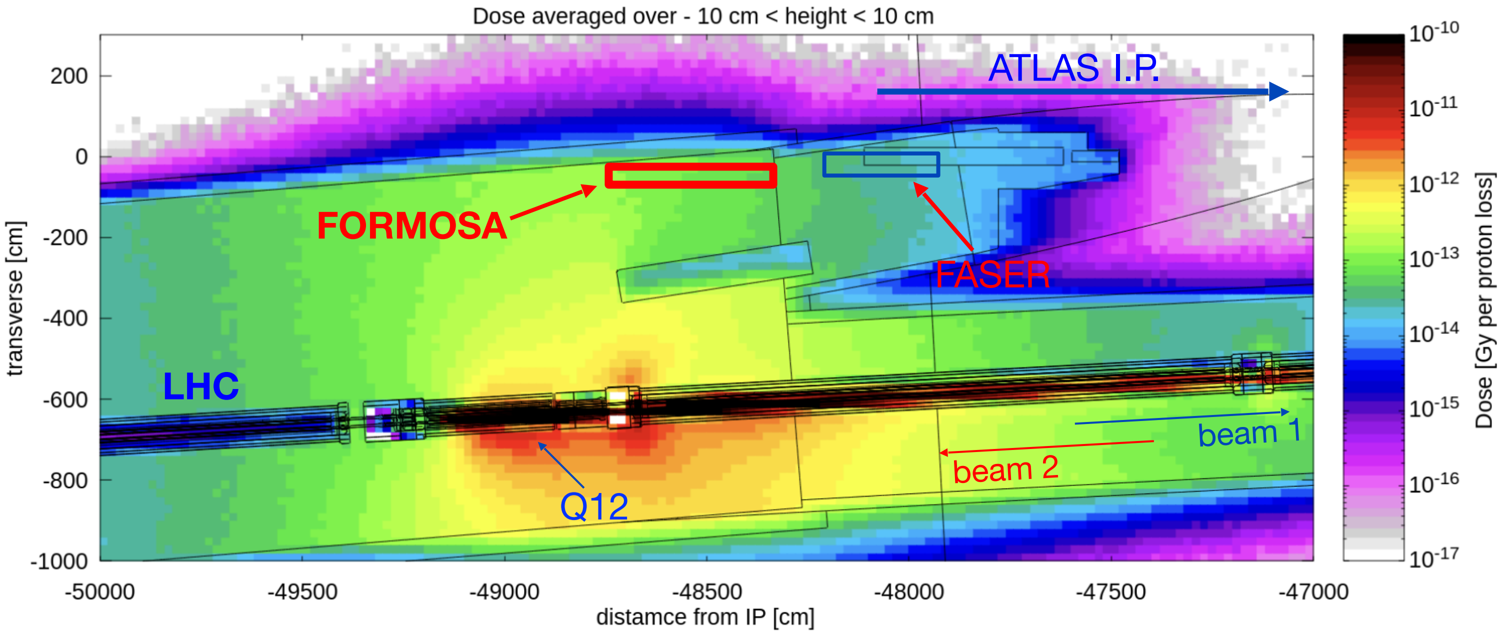

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Side panels

Large front+back muon veto panels

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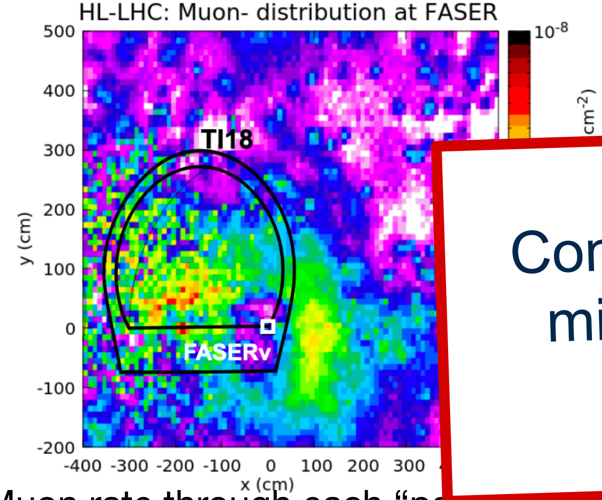
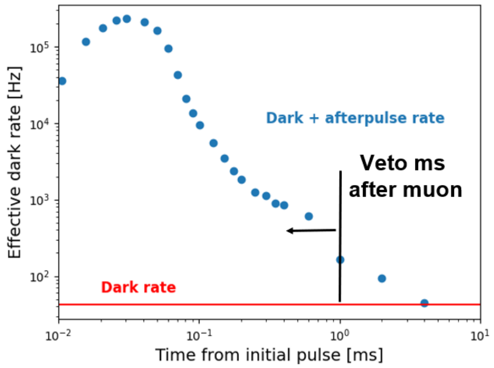


Muon rate through each "path" ~1/40ms

Measure afterpulsing induced by LED pulses



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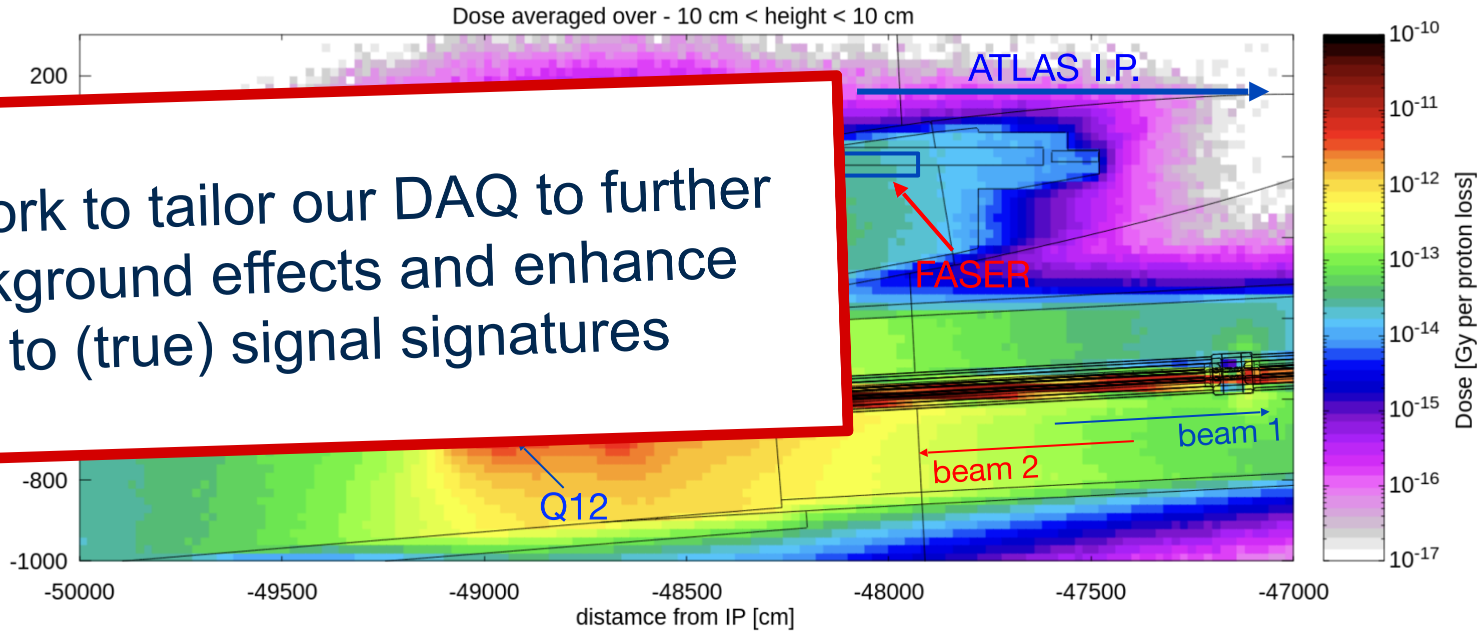

Absolute average dose due to proton loses at Q12 (simulation provided by FASER)

Continuous work to tailor our DAQ to further mitigate background effects and enhance sensitivity to (true) signal signatures

Side panels

Large front+back muon veto panels

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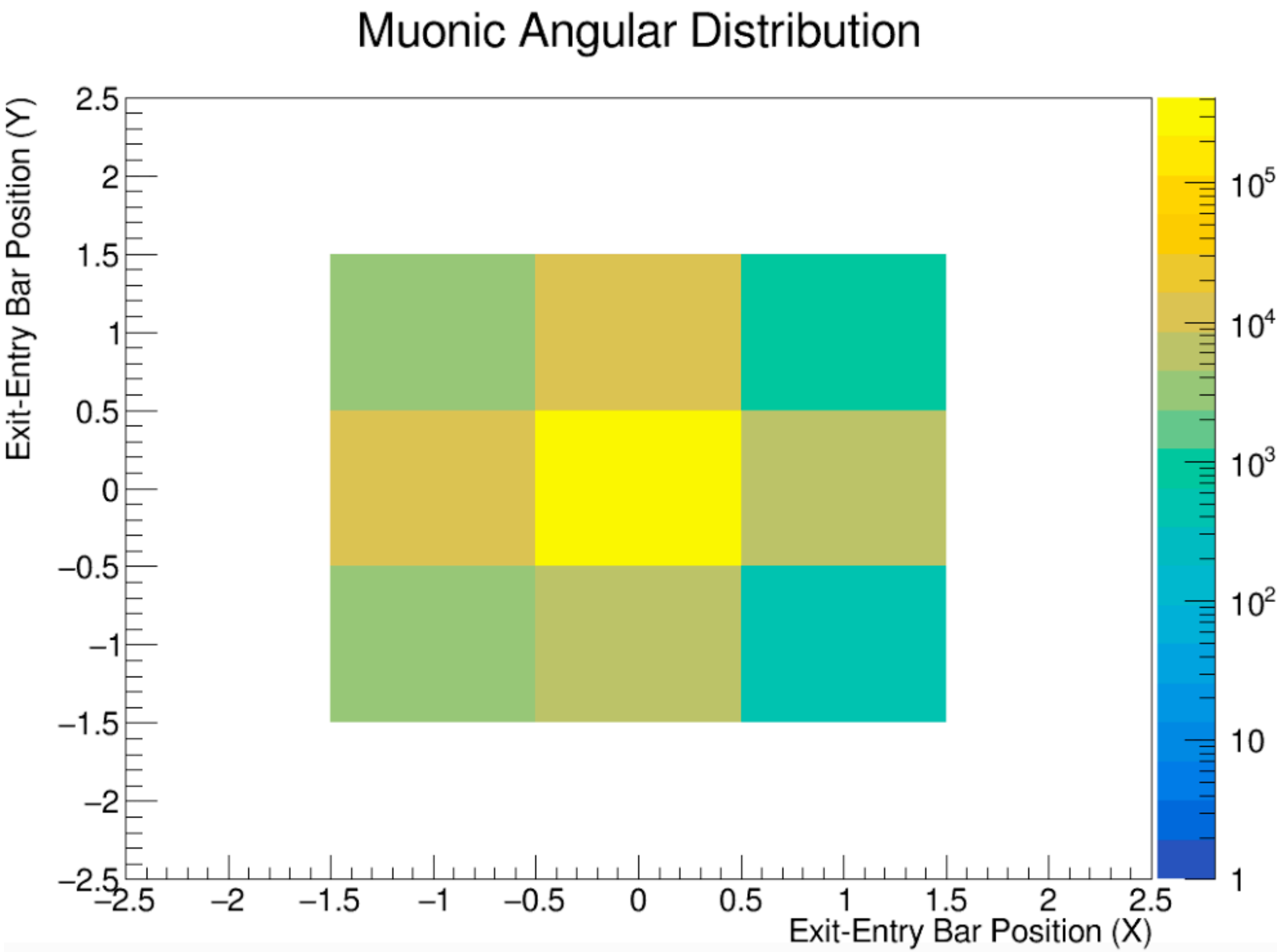
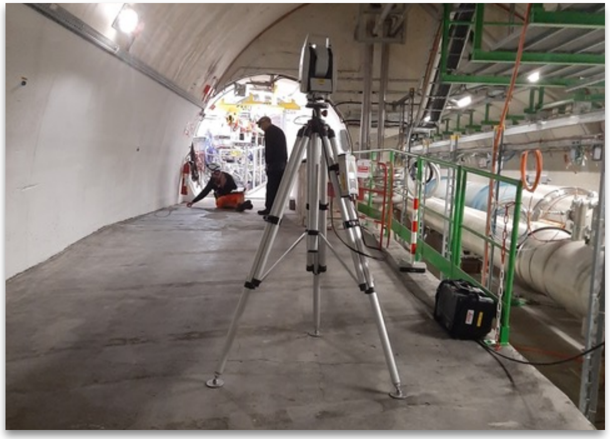
Alignment validation



Checking the distribution of the "exit - entry" bar number of collision muon events

→ LHC collisional data confirms alignment!



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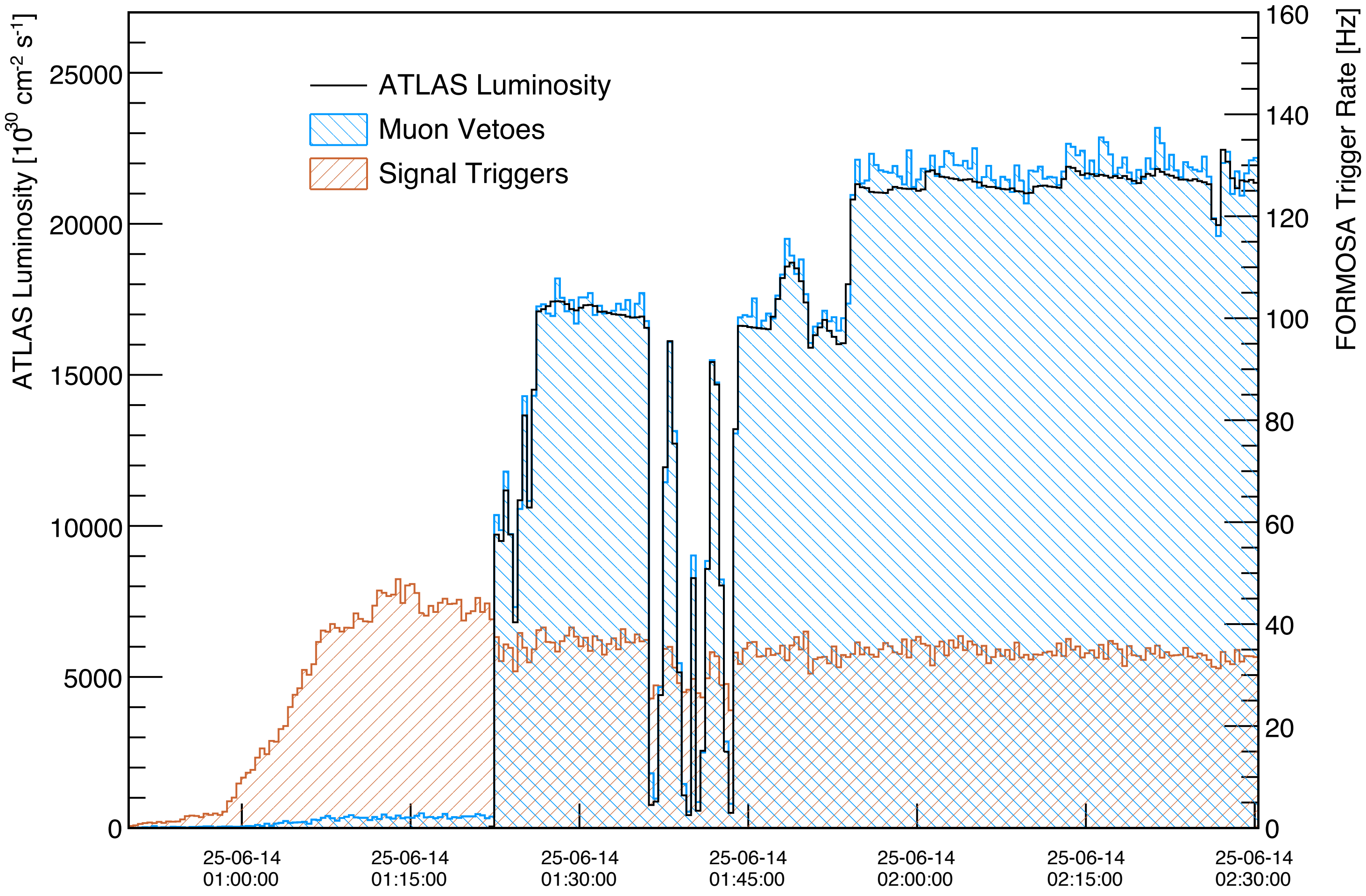
DAQ validation



Data from the 14th of June 2025

Signal triggers stably collecting data

Muons very effectively vetoed!

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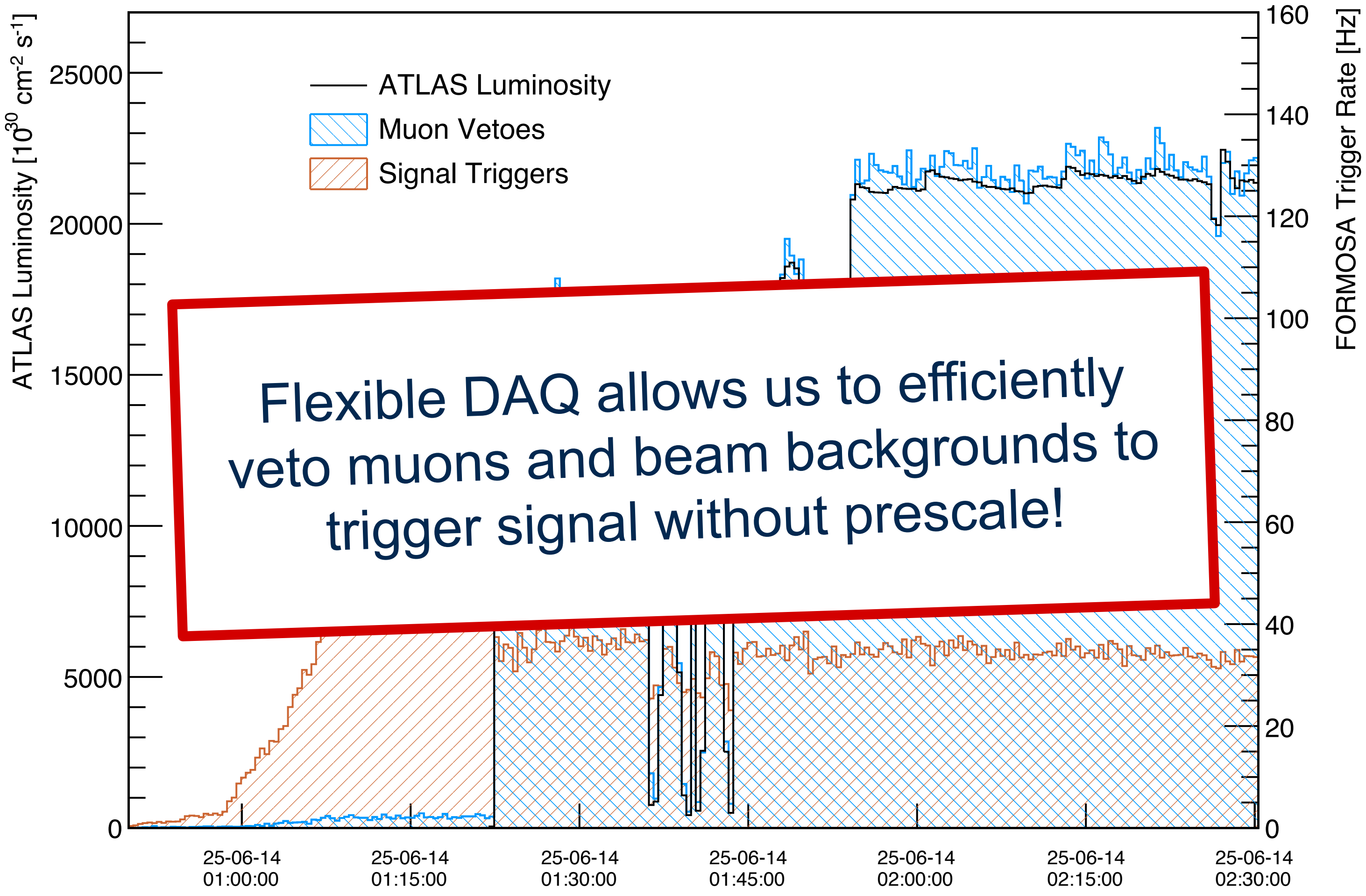

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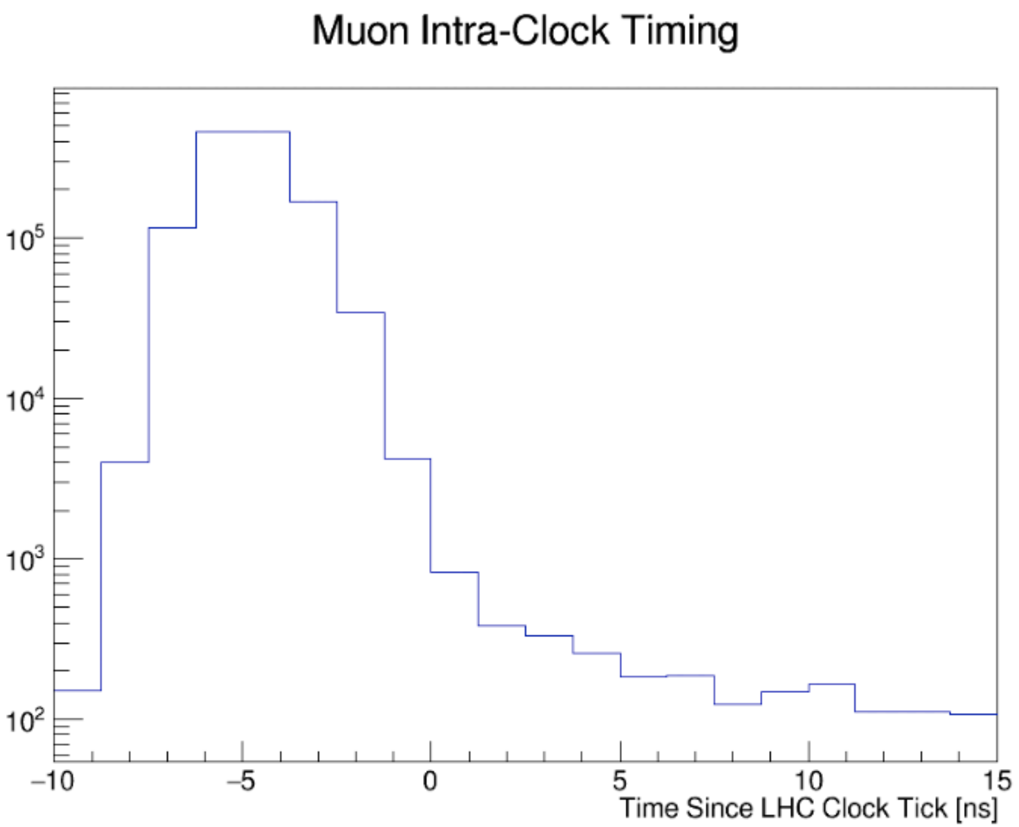
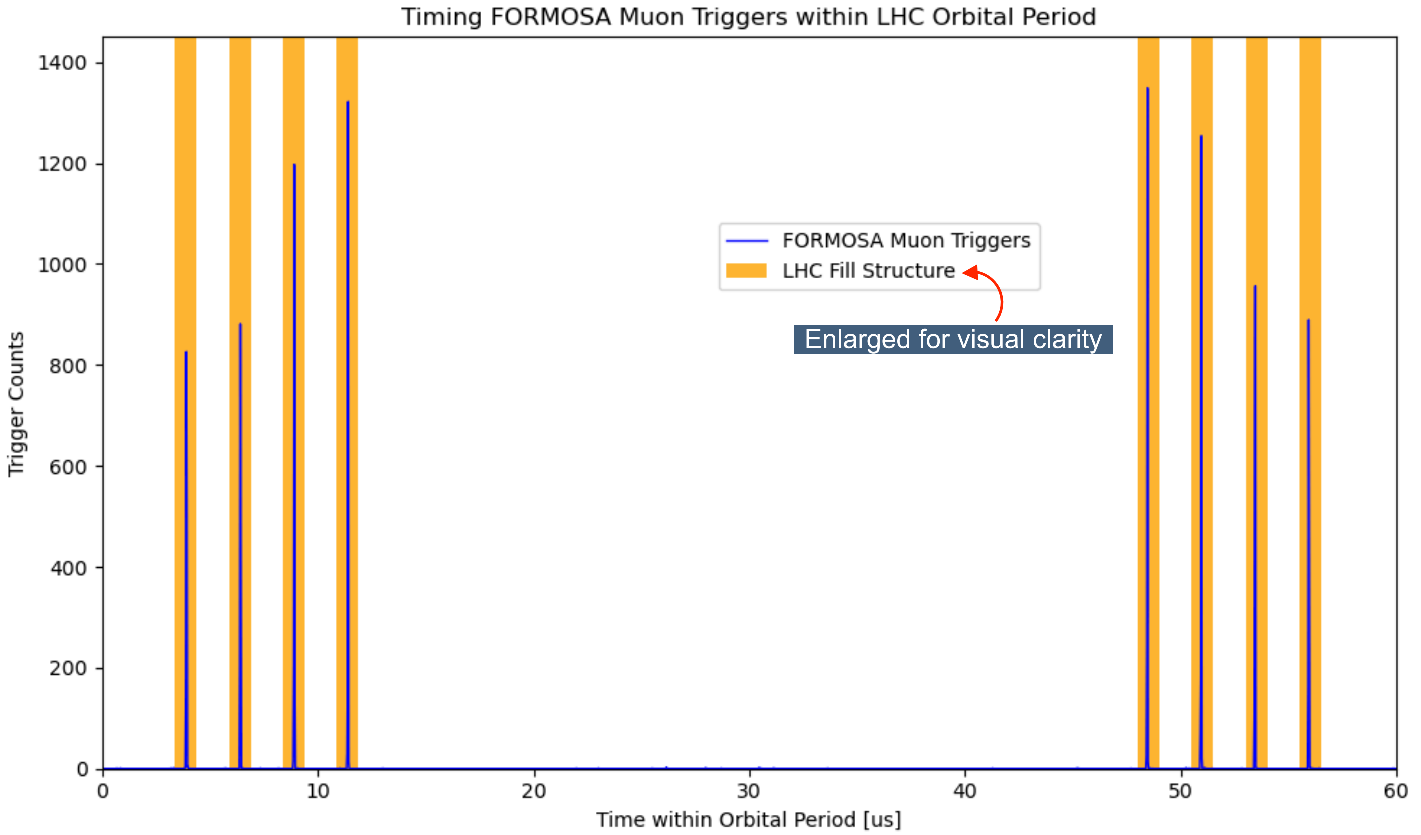
Timing studies



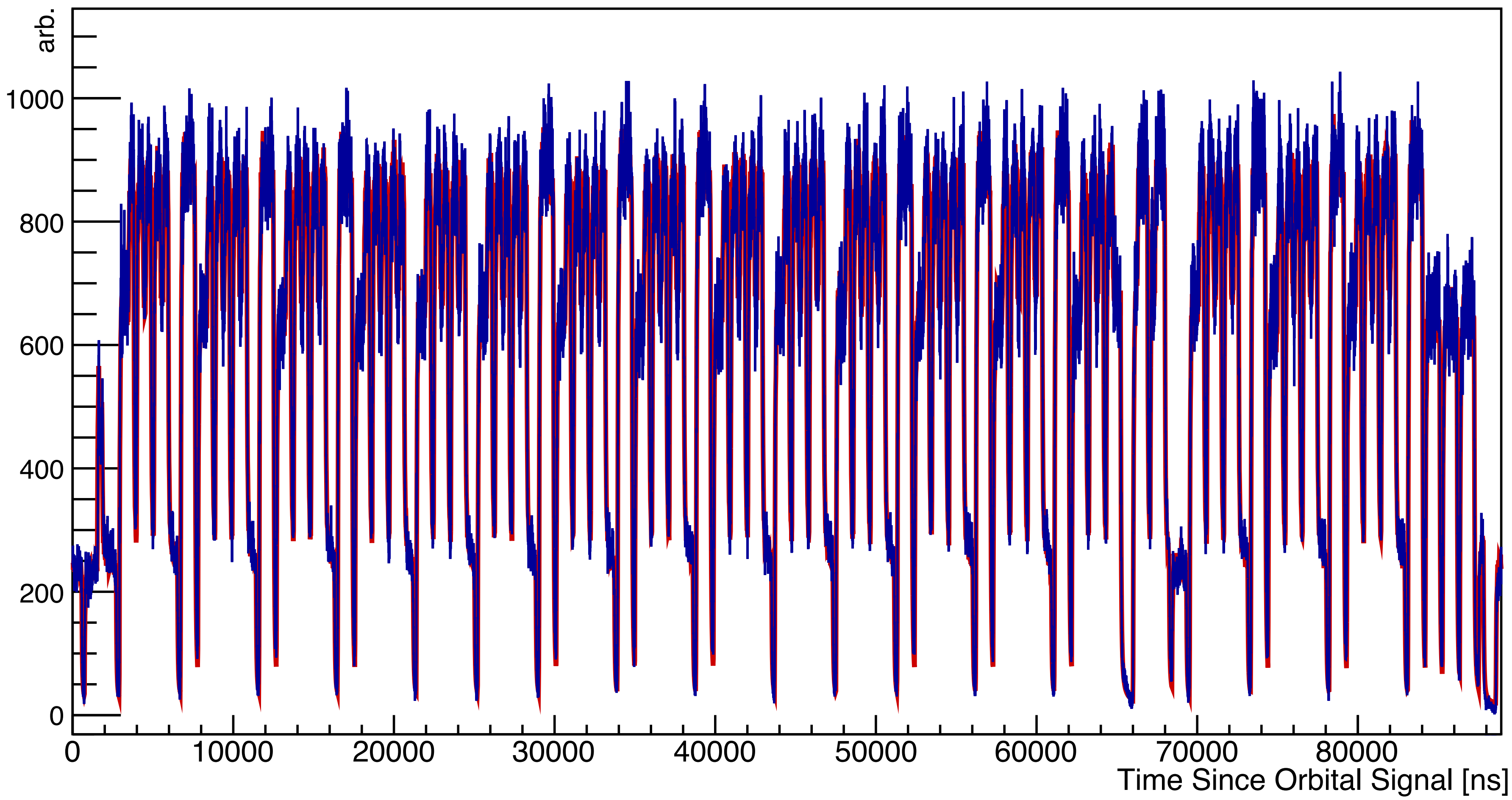
Muon arrival peak **Flat beam background**



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

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

Timing studies: probing the LHC's fill scheme



Fill with 2460b

We have excellent timing resolution!

Next step: to understand our trigger activity relative to the LHC's bunch structure

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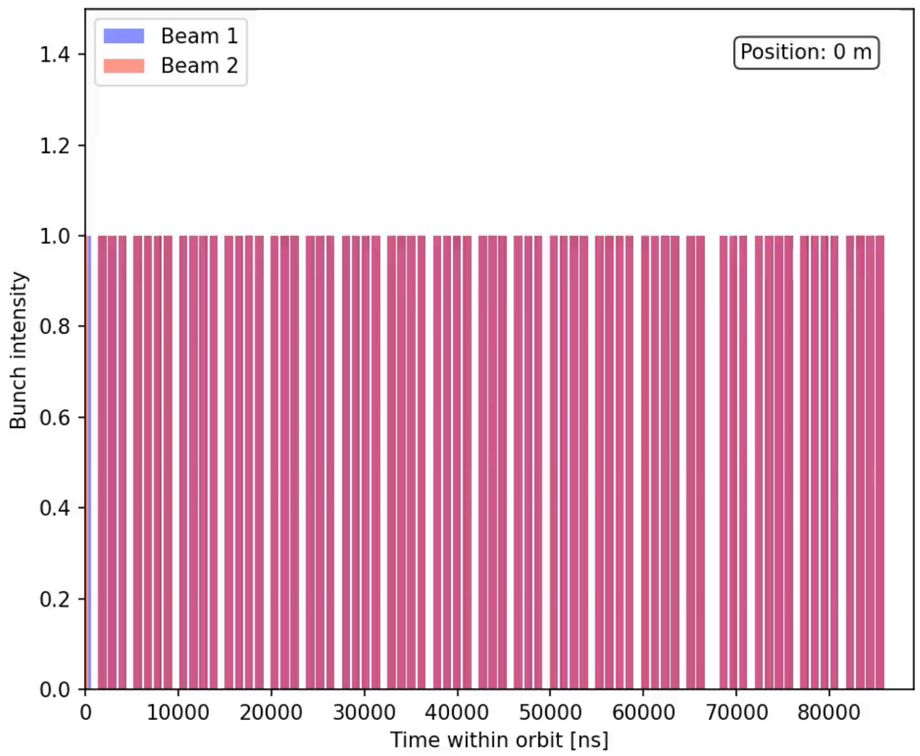
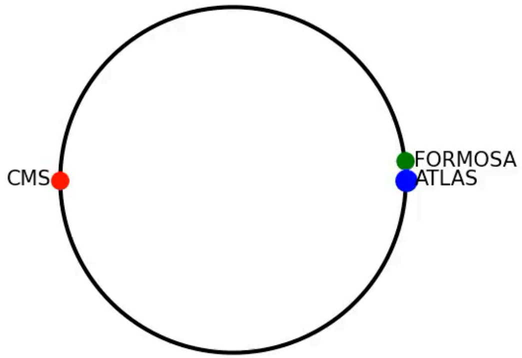
Timing studies: probing the LHC's fill scheme

We want to compare our trigger times since last orbital signal against the LHC's fill scheme and I.P.1's collision scheme.

A first study:

- Track/move the position of all beam 1 and 2 bunches in their corresponding directions
- Each bunch/collision contributes with Landau-distributed trigger activity
- Place the demonstrator at 465m away from I.P.1





$$f(t) = A_1 * \sum_{i=0}^{Beam1} (I_{1,i} \cdot L(t, \mu_i + a_1, \sigma_1)) + A_2 * \sum_{j=0}^{Beam2} (I_{2,j} \cdot L(t, \mu_j + a_2, \sigma_2))$$

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

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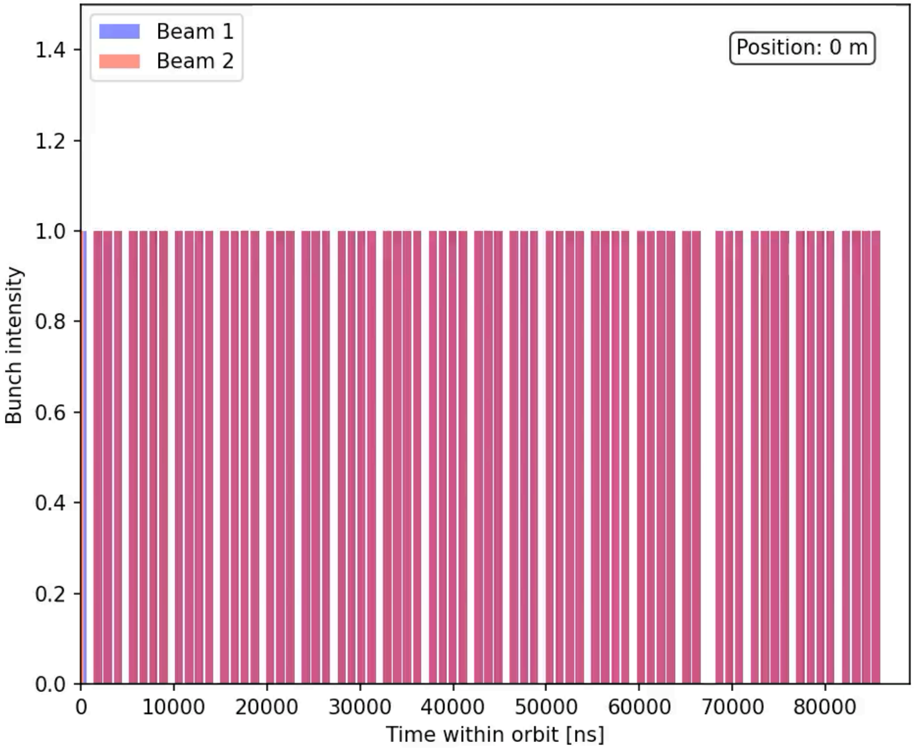

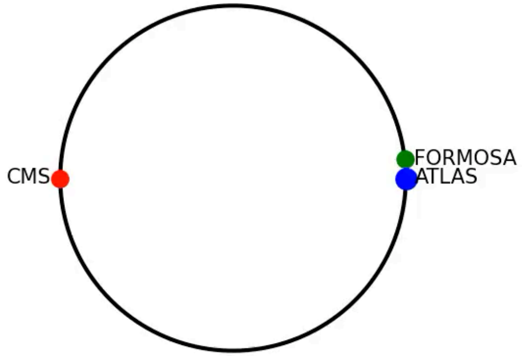

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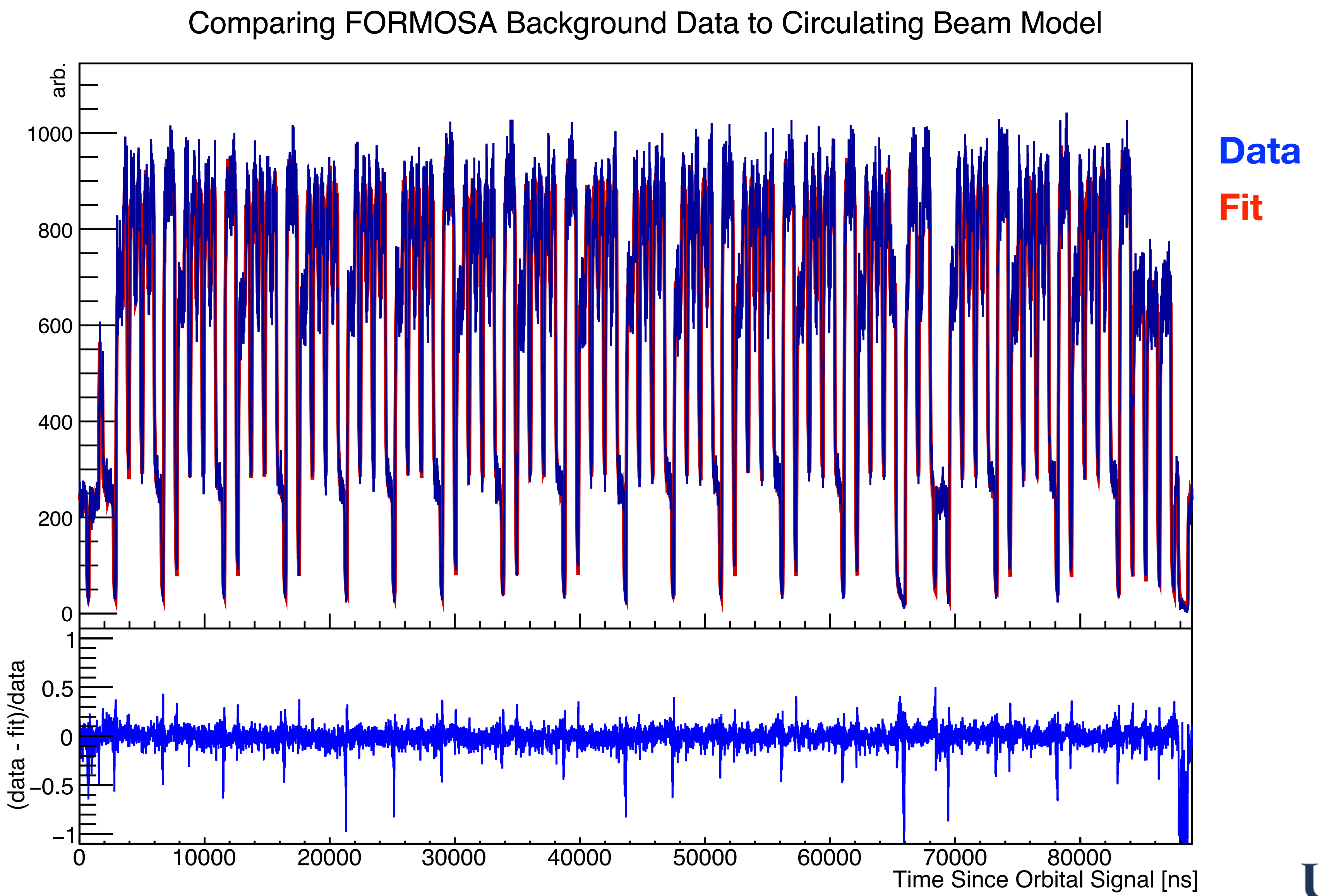
Timing studies: probing the LHC's fill scheme



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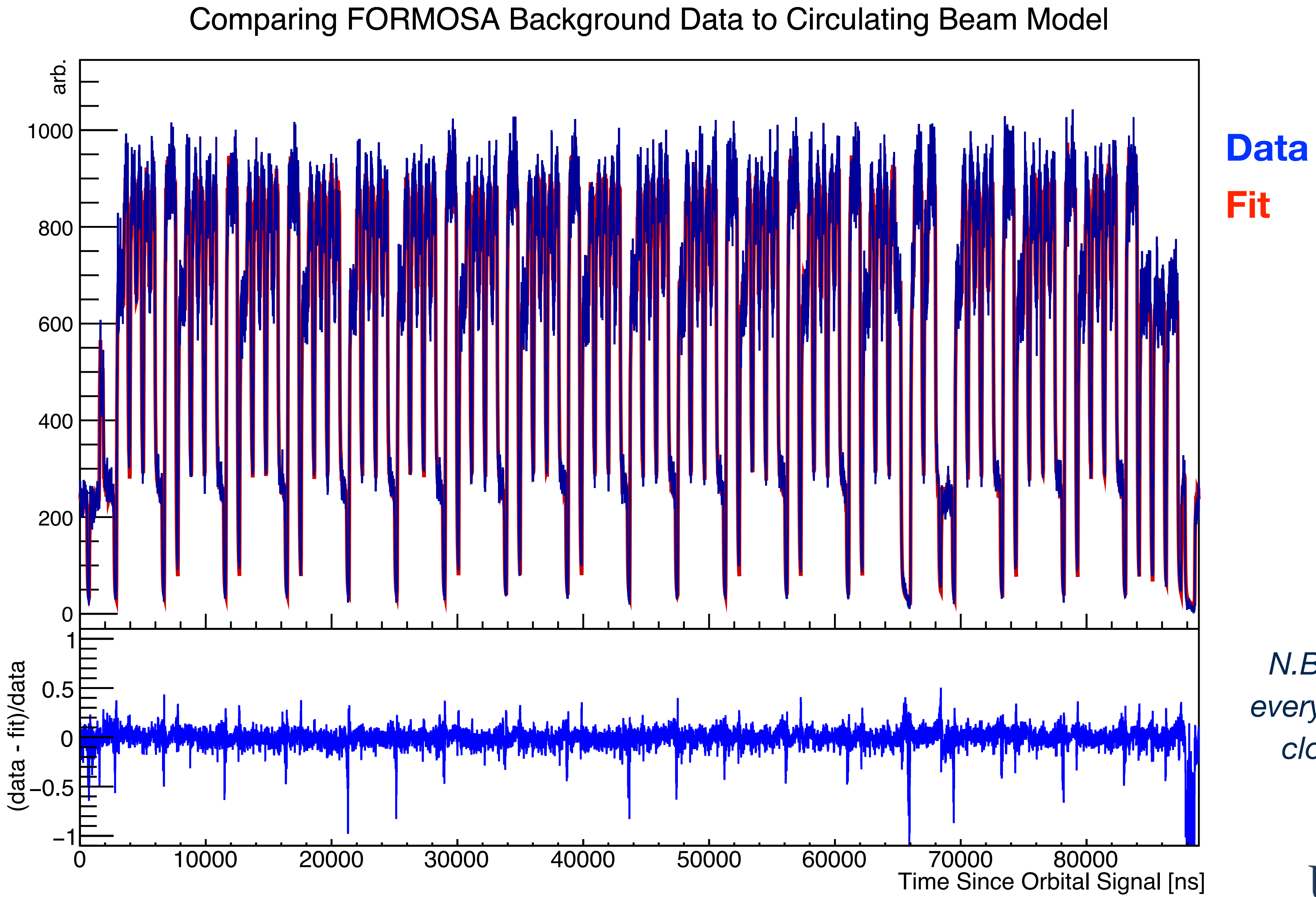


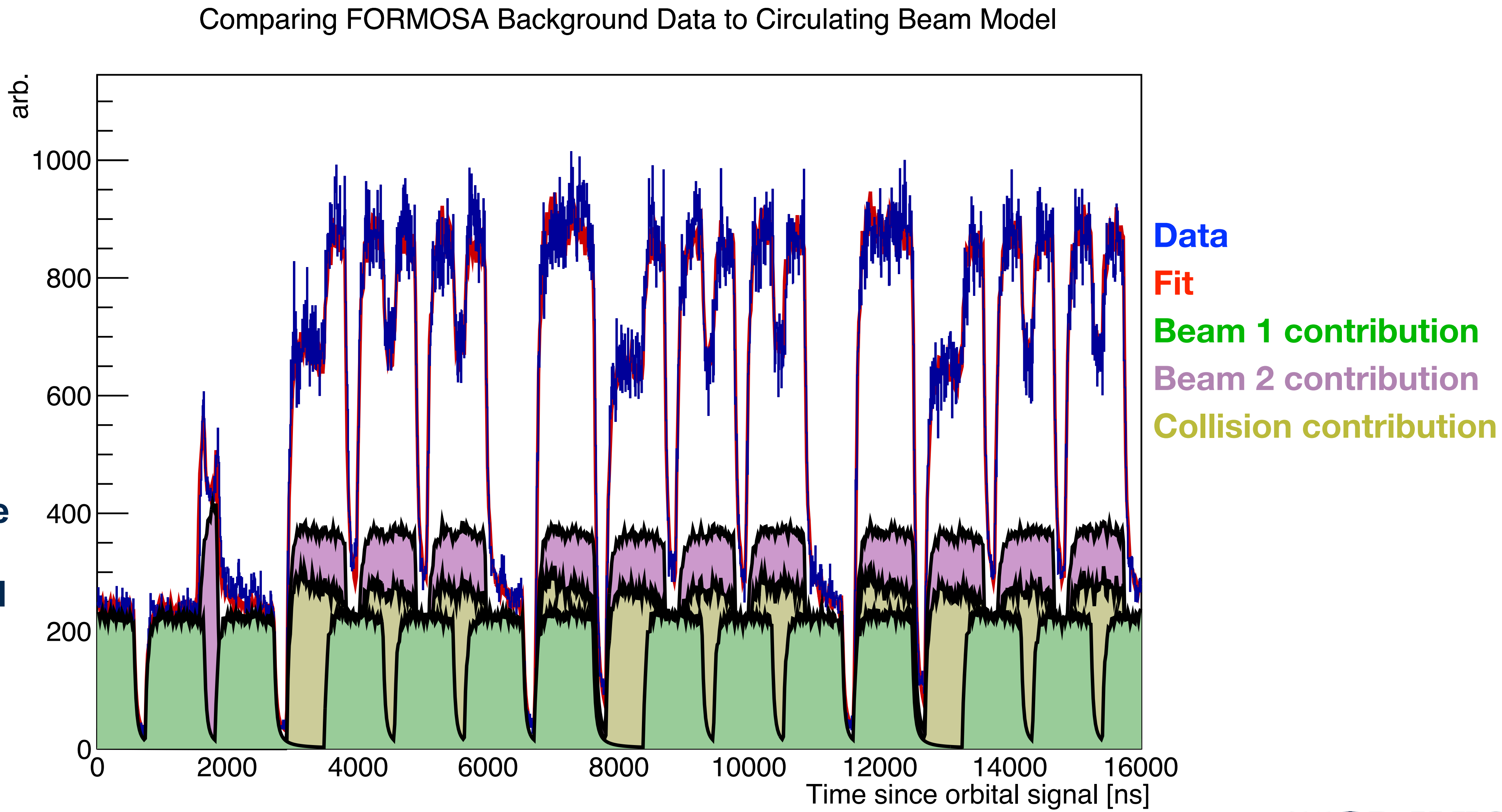
3 contributions (beam 1, beam 2 and I.P.1's collisions) are enough to understand our trigger activity and position ourselves relative to the LHC's orbital signal!

N.B. LHC collisions every 25ns while DAQ clock runs at 8ns!

Timing studies: probing the LHC's fill scheme

Zooming-in and drawing separate contributions hints origin of different signatures

Extremely valuable information for signal/bakcground separation!



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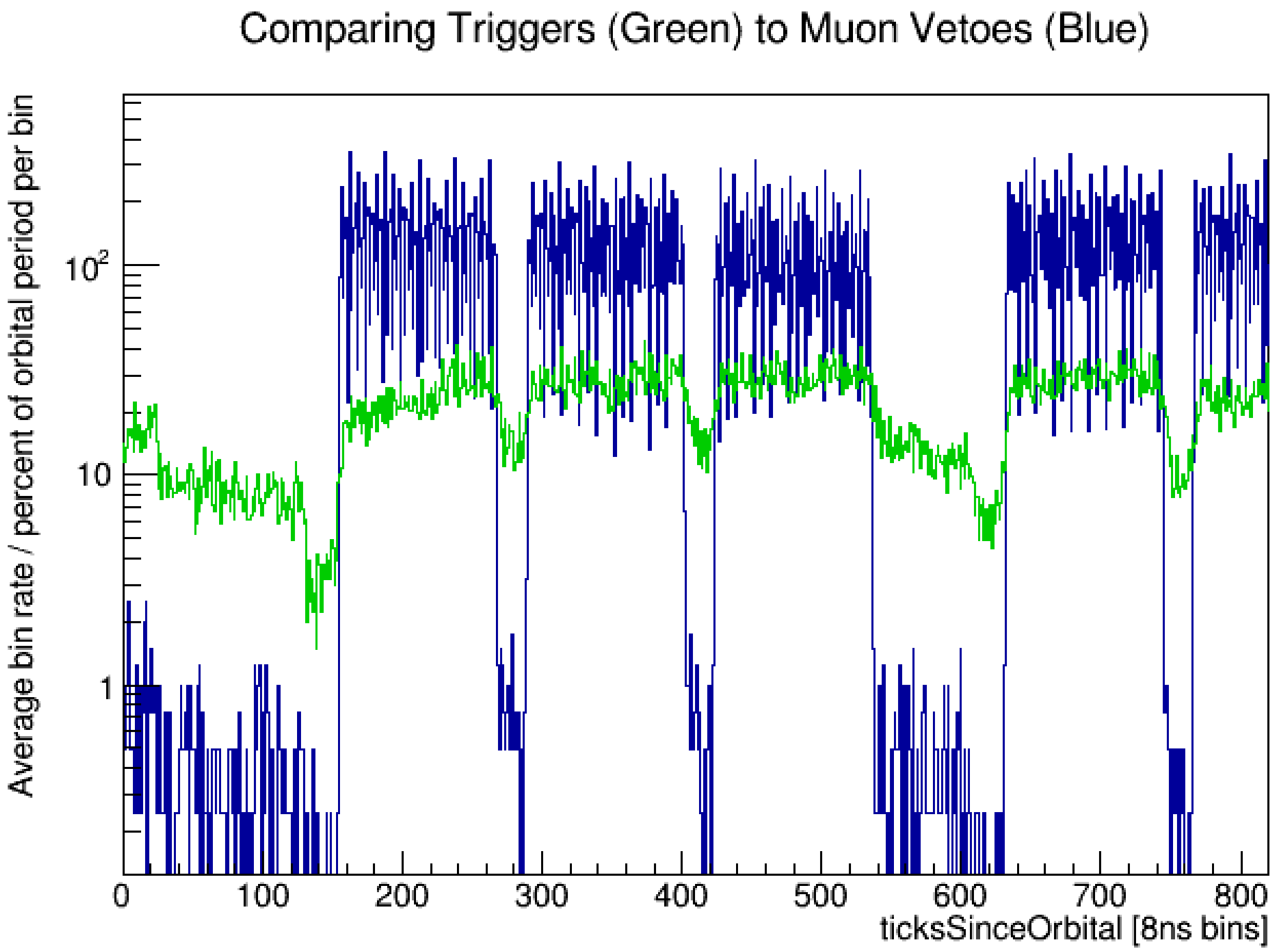
Muon veto studies



Fill with 2460b

N.B. LHC collisions every 25ns while DAQ clock runs at 8ns!

Crucial to determine when physics from collisions may be happening!

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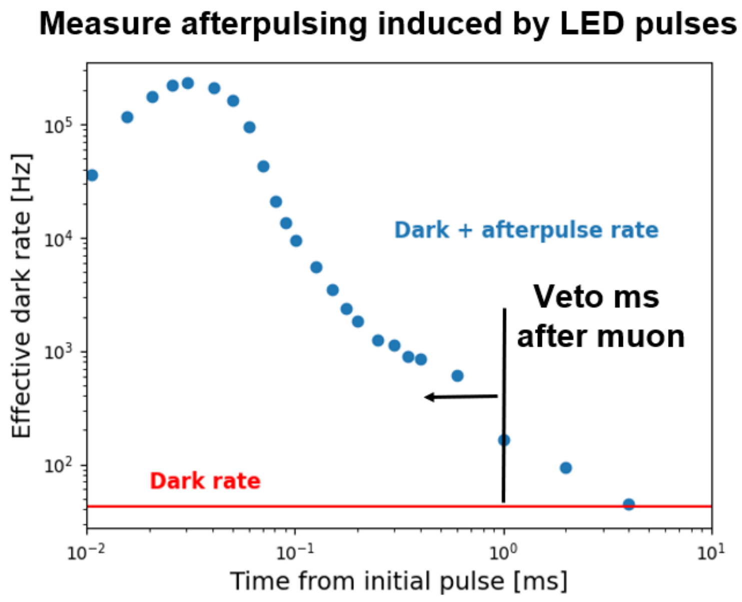
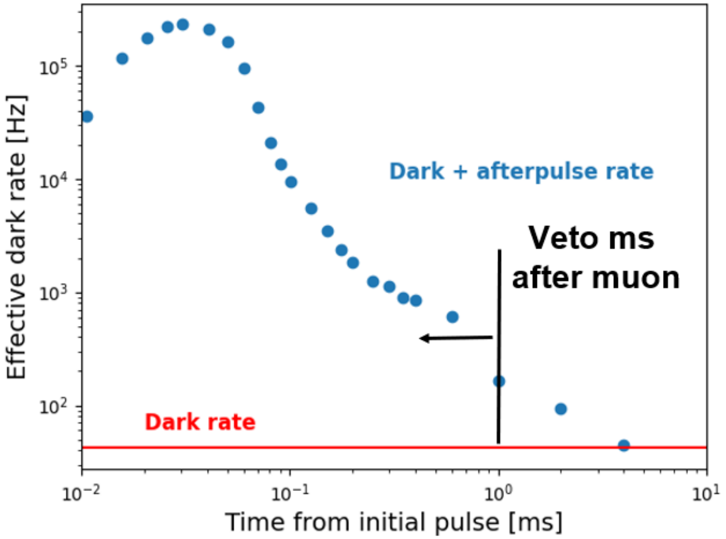
Muon veto and afterpulsing



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



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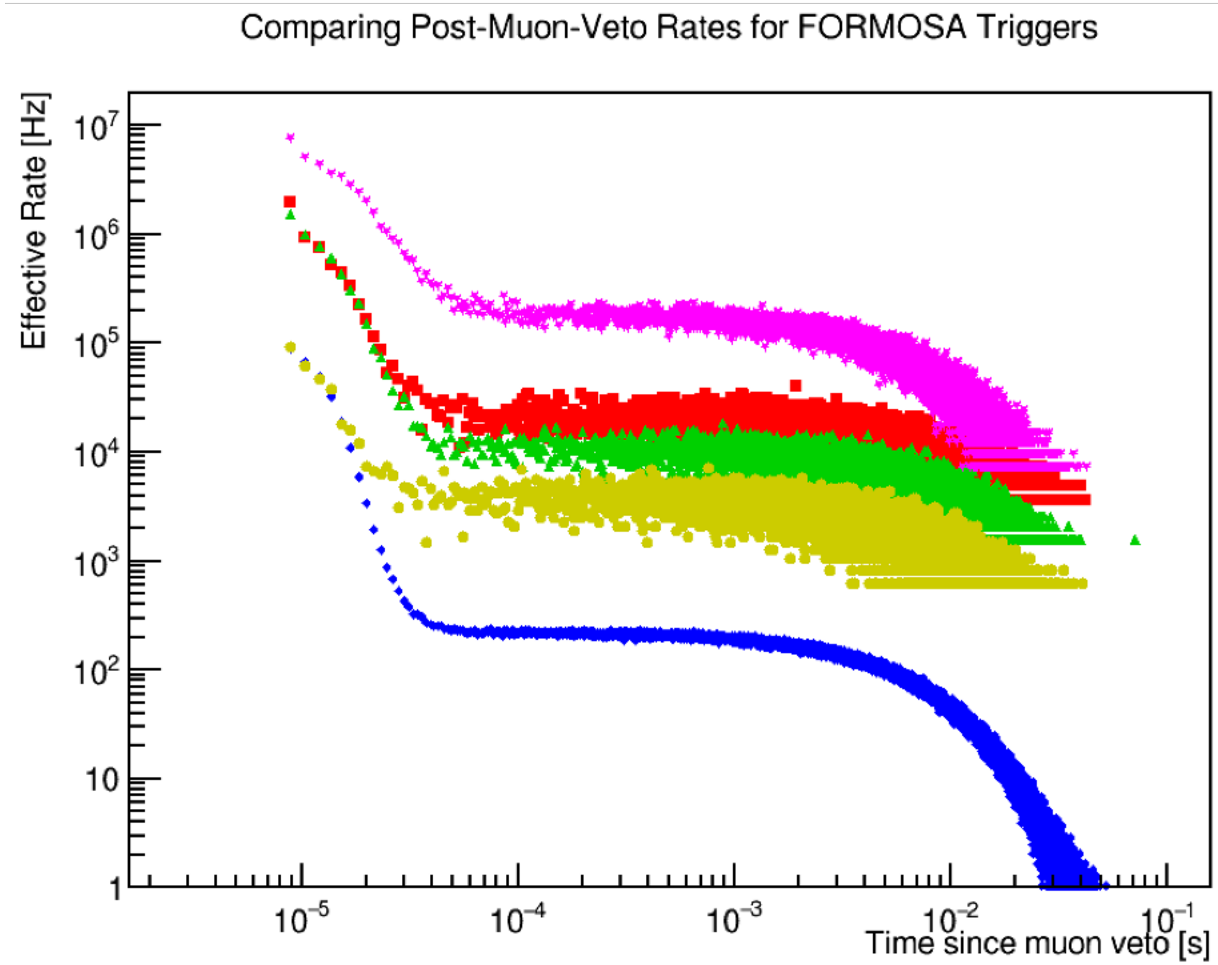

Signal triggers

4Layers

nLayers≥3

nBars≥3

2Layers (both)

Special run with no muon deadtime

Overall scaling still in progress

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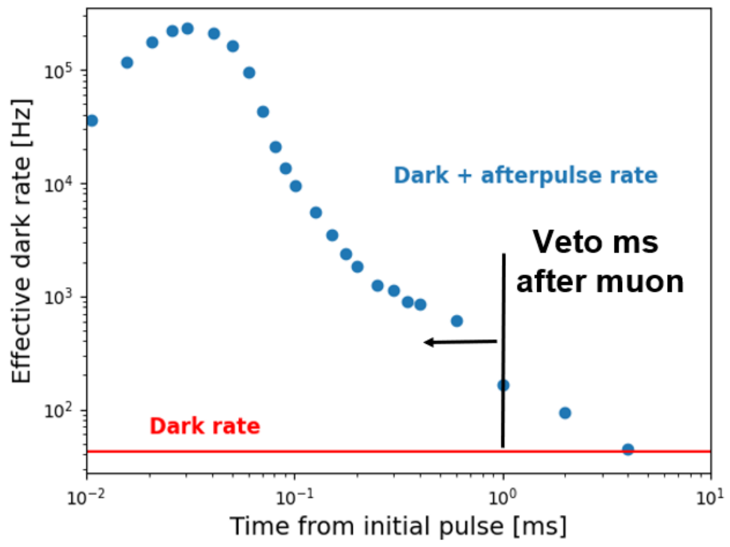
Muon veto and afterpulsing

Measure afterpulsing induced by LED pulses



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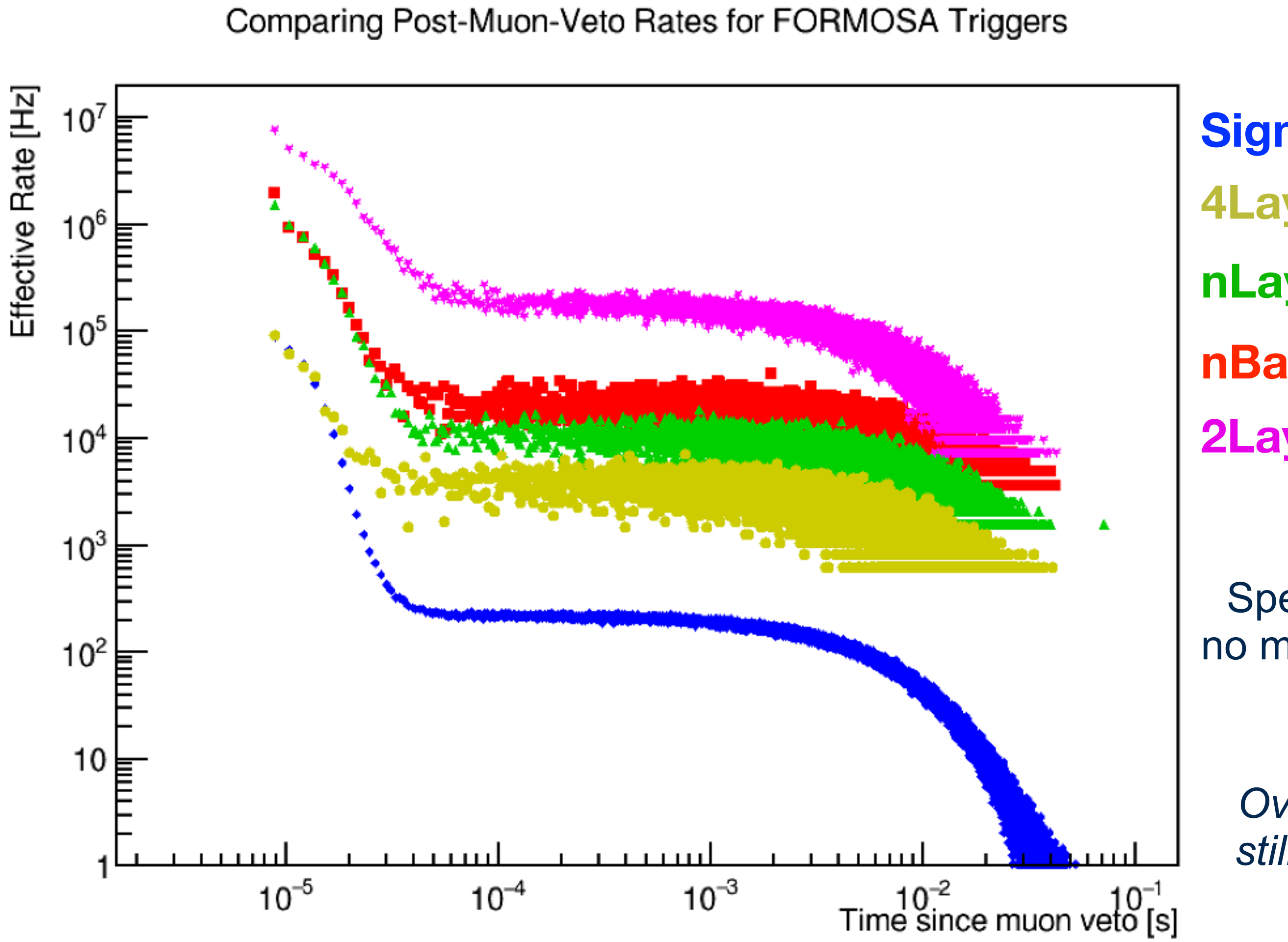

Signal triggers

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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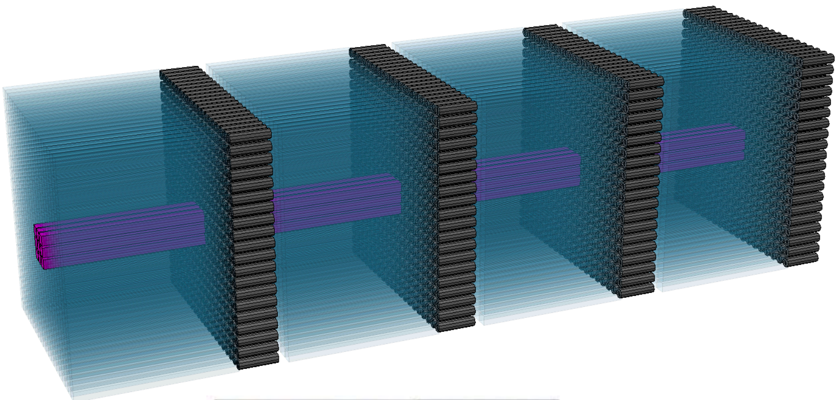
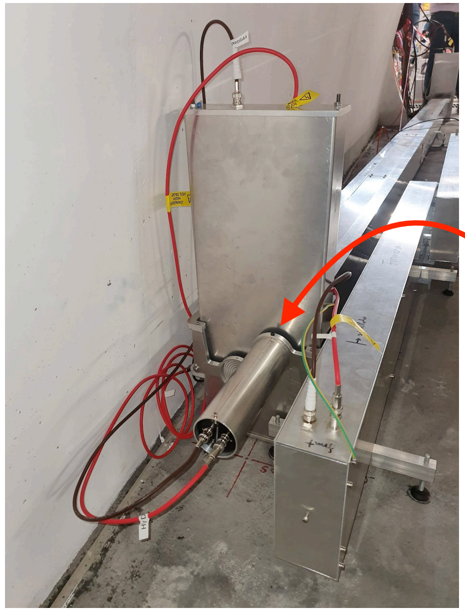
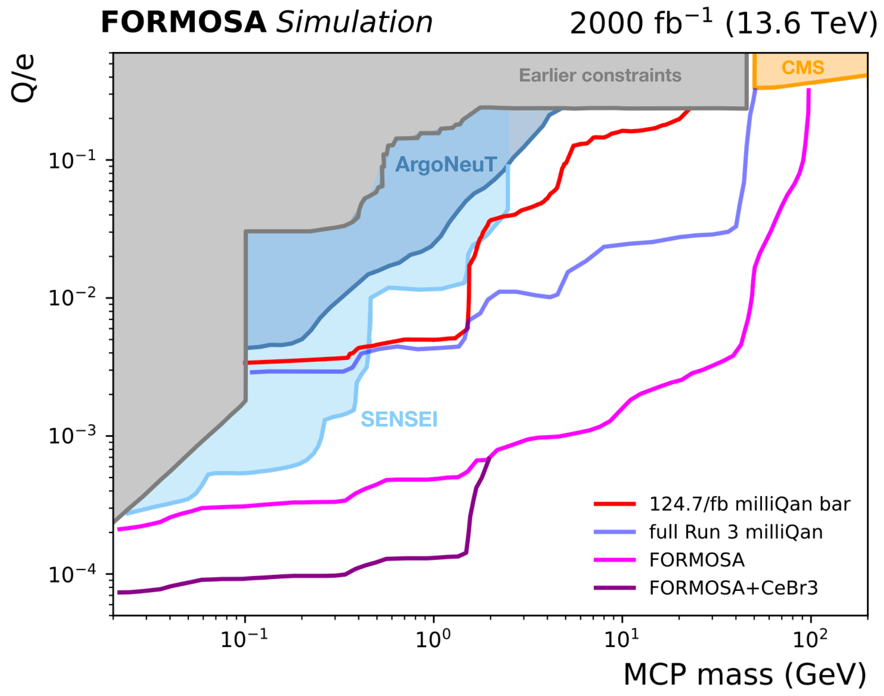
FORMOSA: CeBr3 module





Incorporated CeBr3 module into demonstrator in Sept 2024

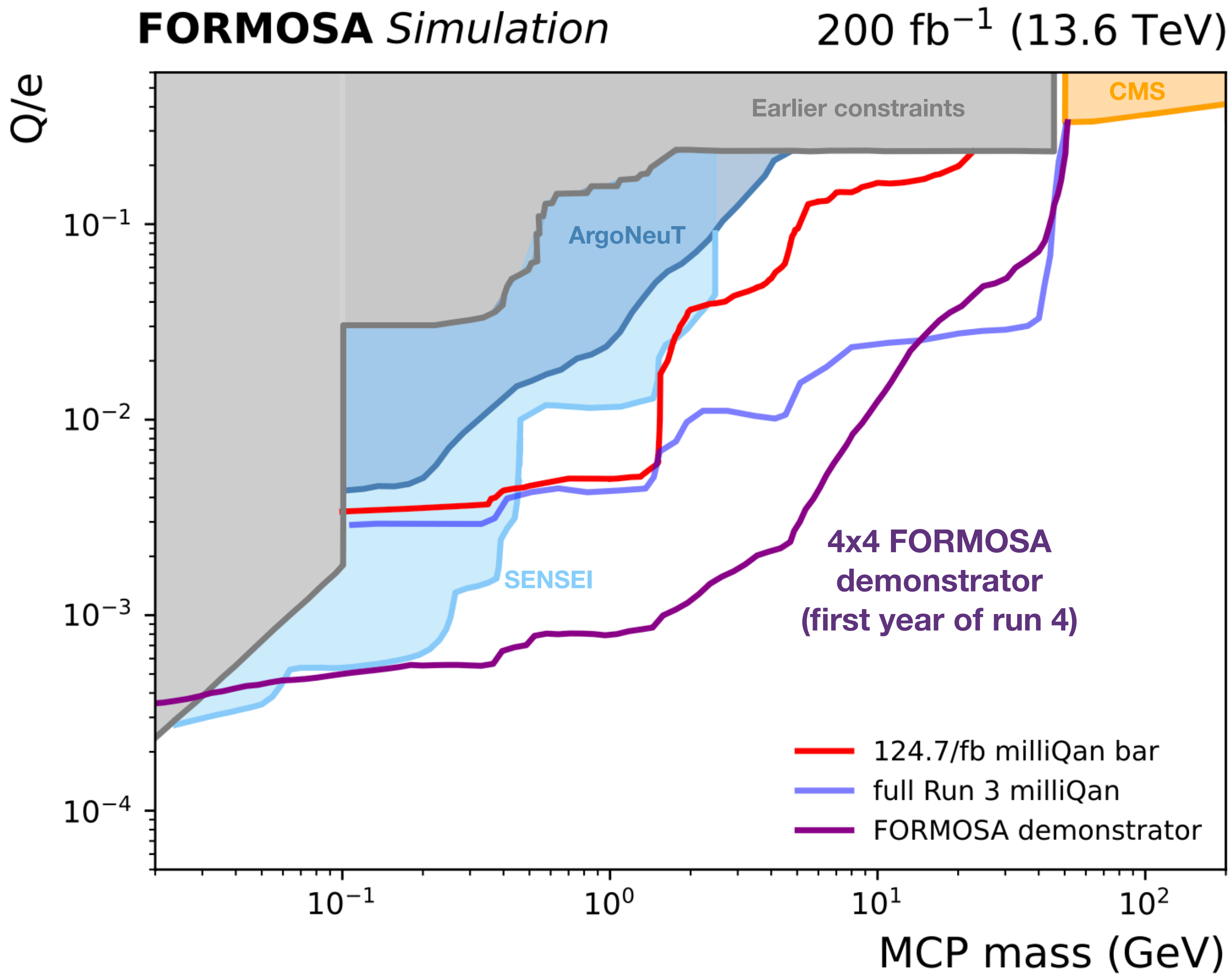


Investigate feasibility of FORMOSA subdetector made from CeBr3

- 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

FORMOSA demonstrator sensitivity



Hermetic rejection panels added in earlier this year: will attempt search with 2025 LHC data!

Expand demonstrator size for early HL-LHC if funding allows

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The FORMOSA collaboration

Members from 8 institutions and growing!

This speaker supported by funding from DOE Office of Science

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Summary

- Demonstrator installed last year and taking data through 2024
- DAQ (hardware and firmware) validated
  - Alignment with L.O.S. to I.P. validated
  - Verified we are measuring physics correlated to LHC activity
  - Capable of identifying and vetoing online muons generated by I.P. collisions
  - Intra-clock timing proving useful for understanding activity and backgrounds
- Hermetic side and top panels installed to improve background understanding
- $CeBr_3$ test module installed to carry out extended studies
- Demonstrator currently taking data stably!

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End

Backup

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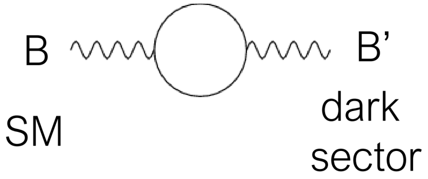
Why millicharged particles?

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

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

massless “dark photon” — “dark fermion” with mass M_{mCP} , charge e' — mixing term



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

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

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

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

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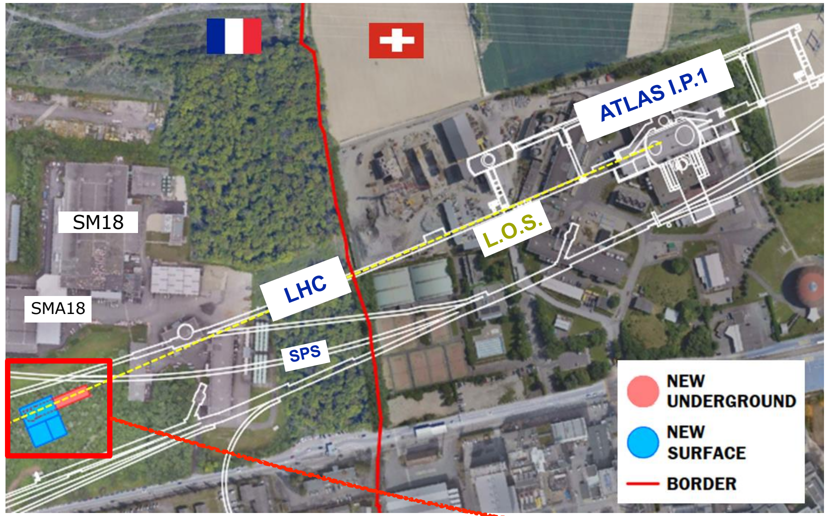
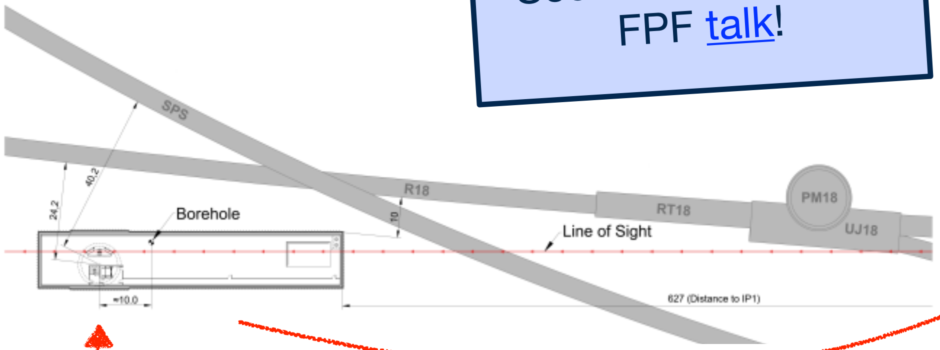
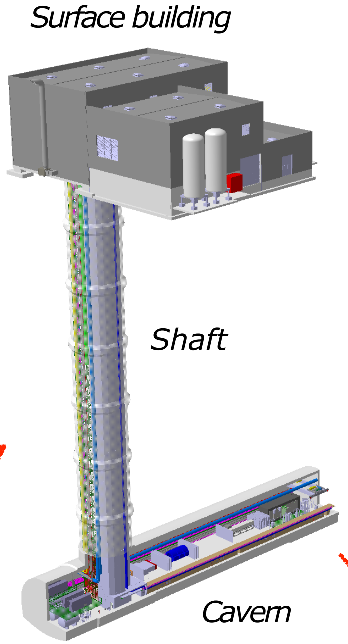
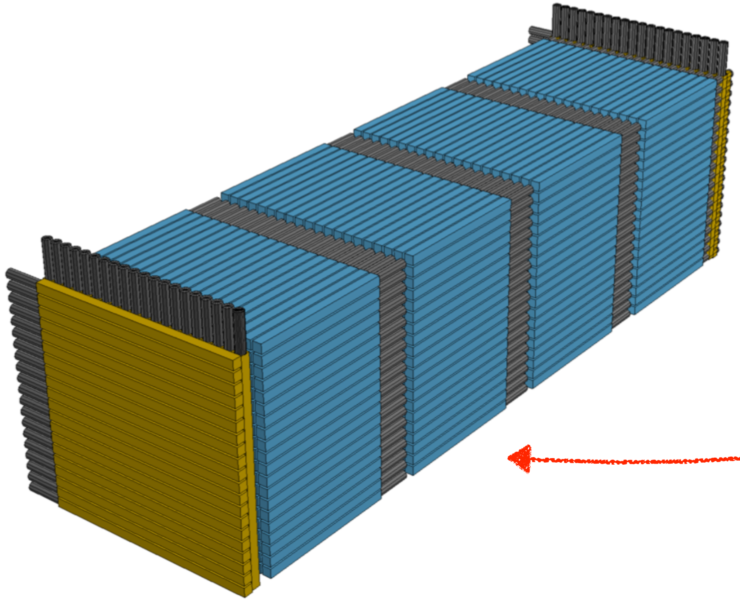
FORMOSA at the FPF

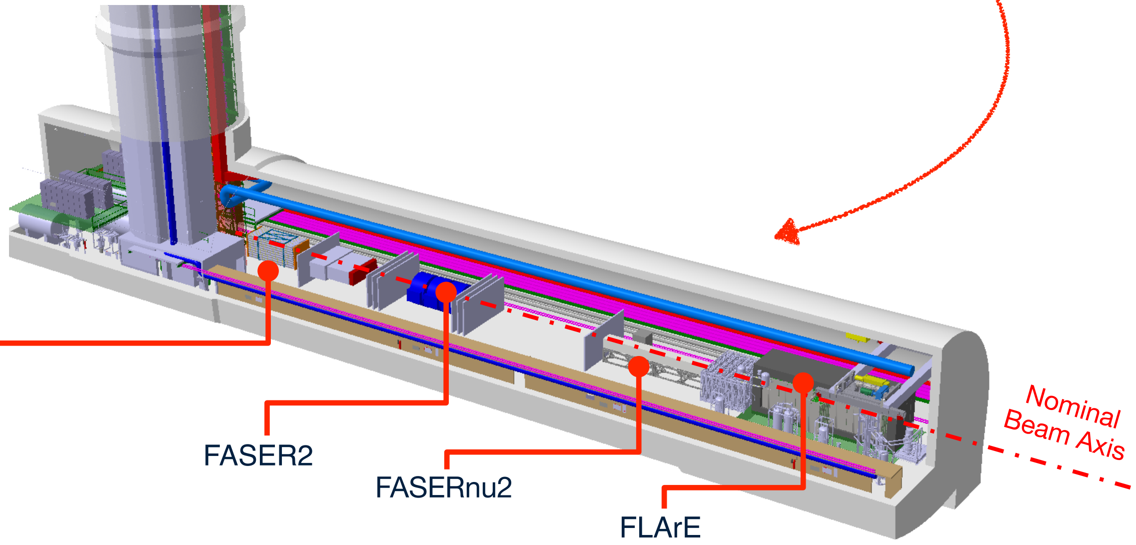




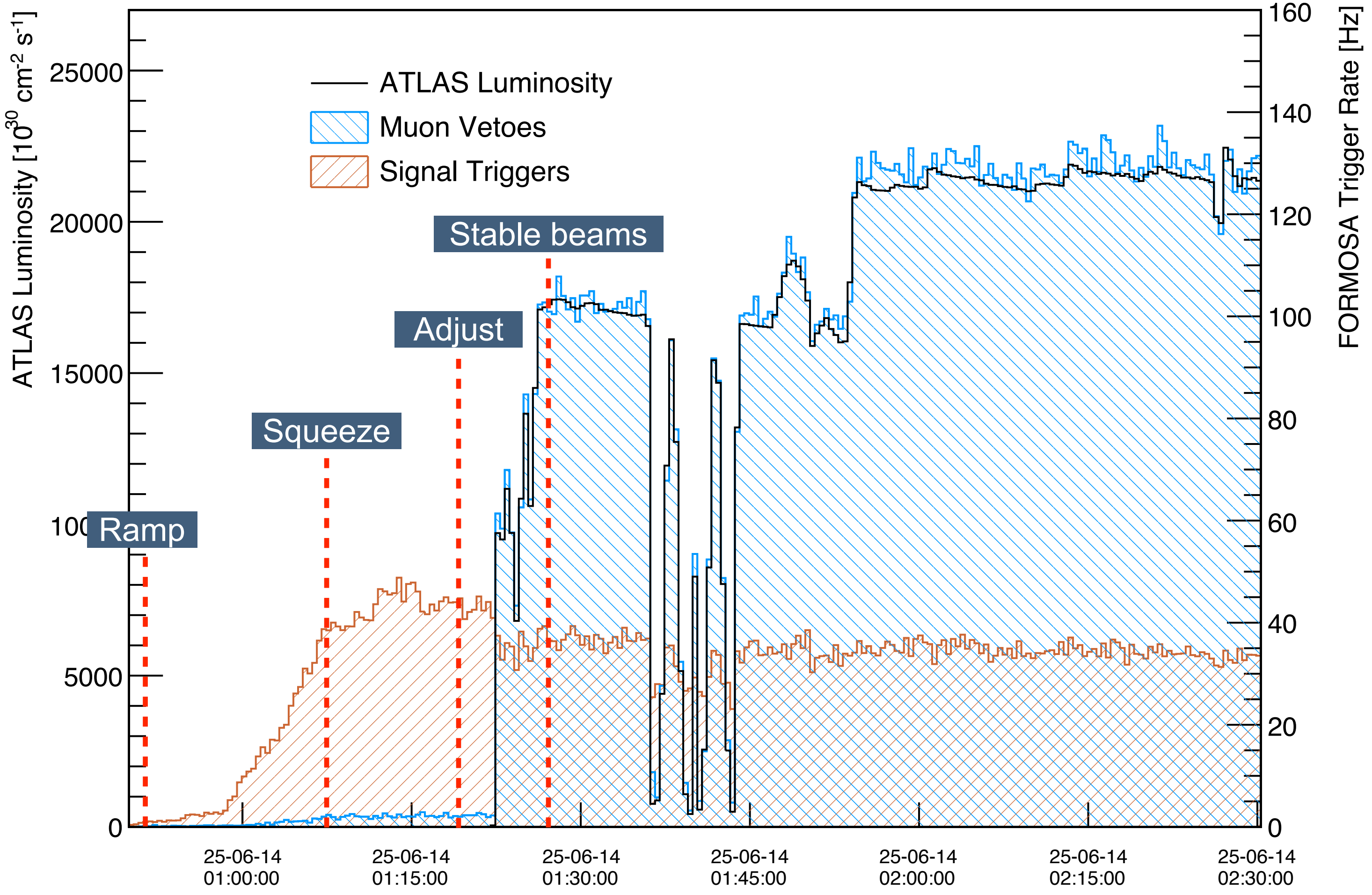
See Akitaka Ariga's FPF talk!







DAQ validation



Data from the 14th of June 2025

Signal triggers stably collecting data

Muons very effectively vetoed!

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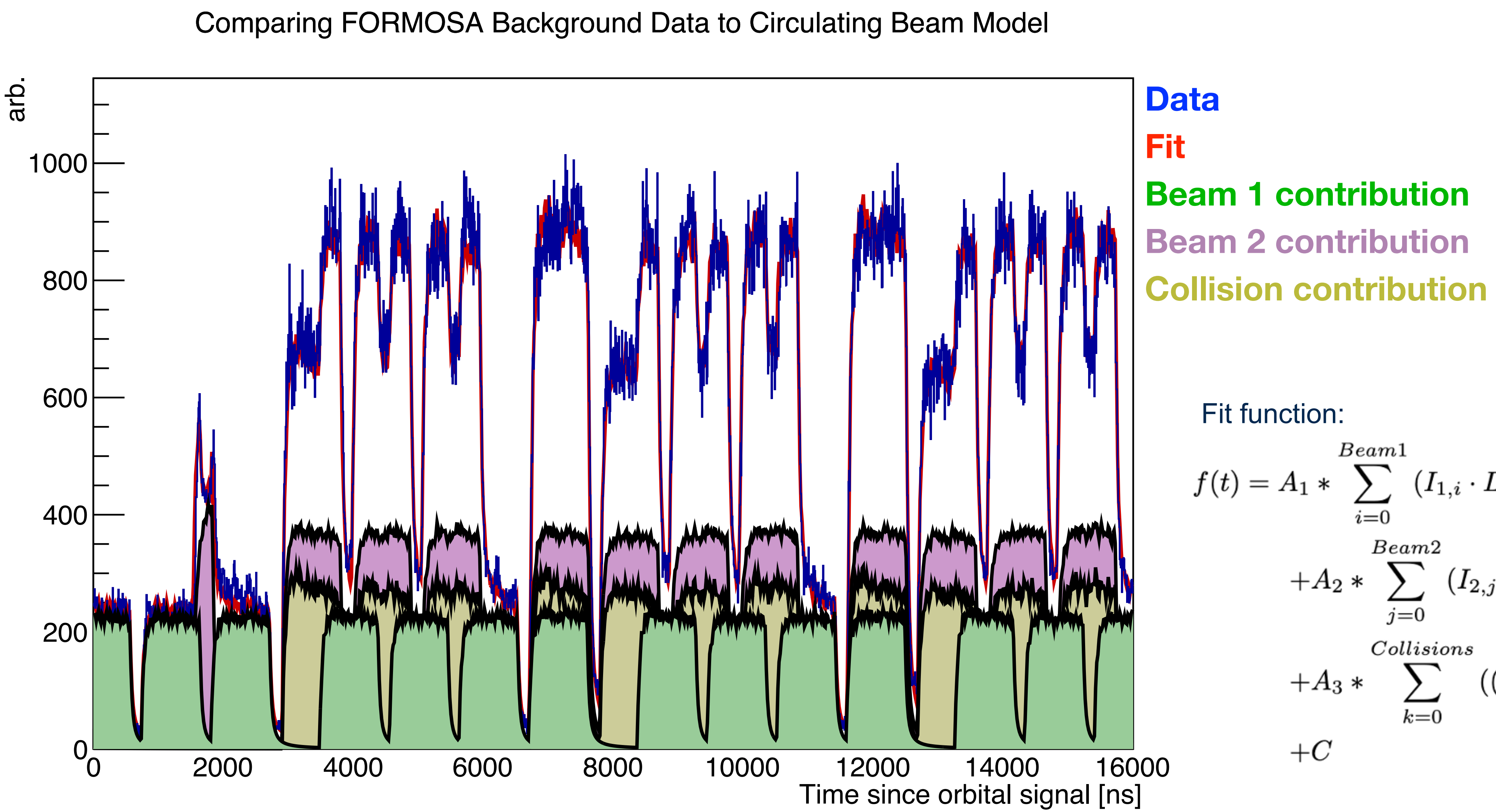
Timing studies: probing the LHC's fill scheme



Fit function:

$$f(t) = A_1 * \sum_{i=0}^{Beam1} (I_{1,i} \cdot L(t, \mu_i + a_1, \sigma_1))$$
$$+ A_2 * \sum_{j=0}^{Beam2} (I_{2,j} \cdot L(t, \mu_j + a_2, \sigma_2))$$
$$+ A_3 * \sum_{k=0}^{Collisions} ((I_{1,k} \times I_{2,k}) \cdot L(t, \mu_k + a_3, \sigma_3))$$
$$+C$$

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