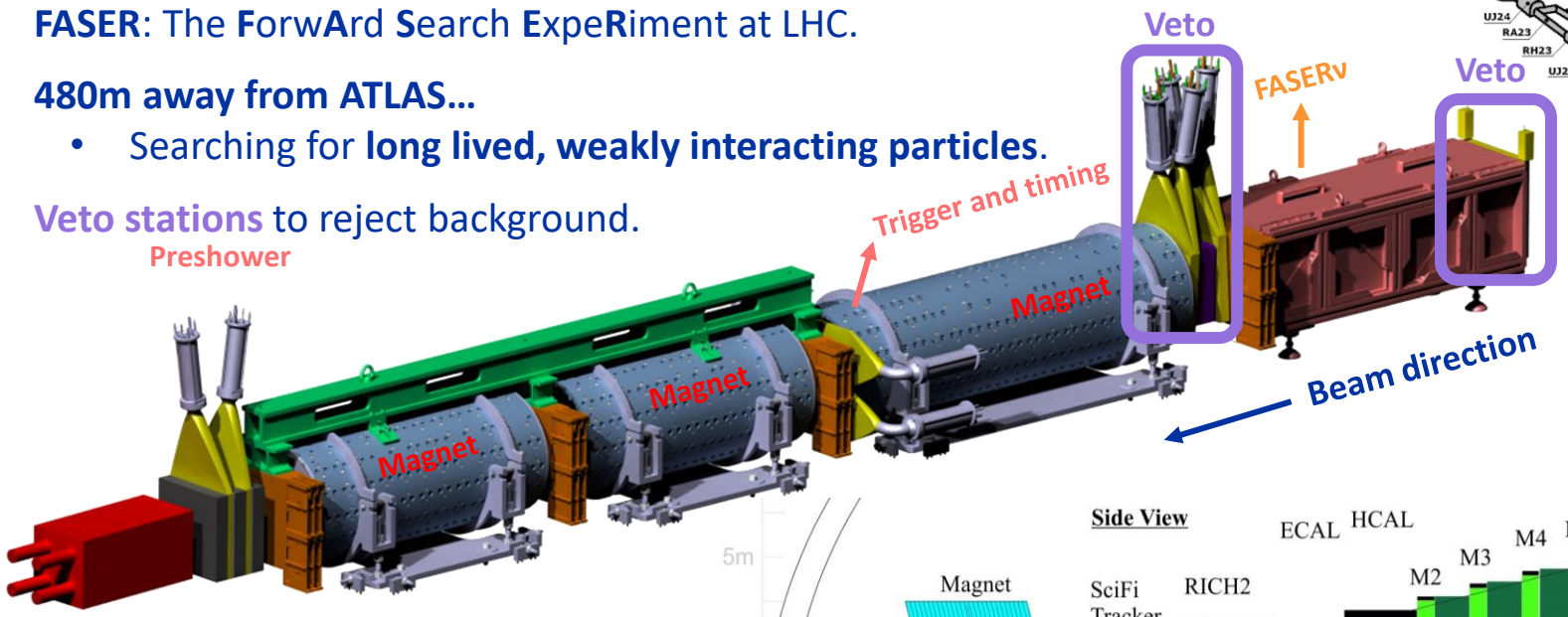
Photodetector Upgrades for HL-LHC: Scintillating Fibre R&D for Future Detectors and the FASER Run 4 Upgrade

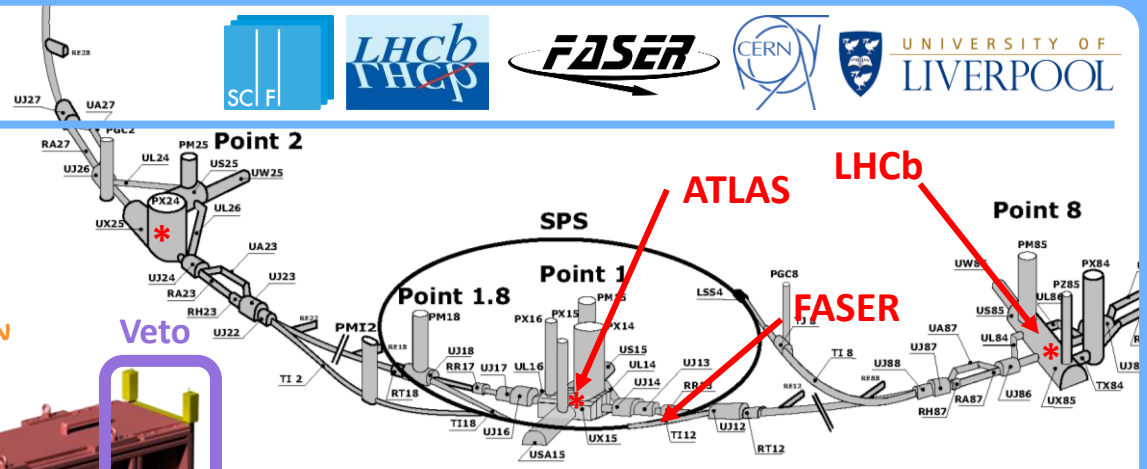
Annabelle Marie Parry

Supervisors:
Brian Petersen (CERN), Sune Jakobsen (CERN), Monica D'Onofrio (Liverpool), Karol Hennessy (Liverpool), Niels Tuning (NIKHEF)

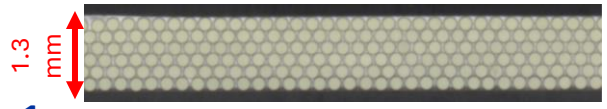
Forward Detectors at the LHC

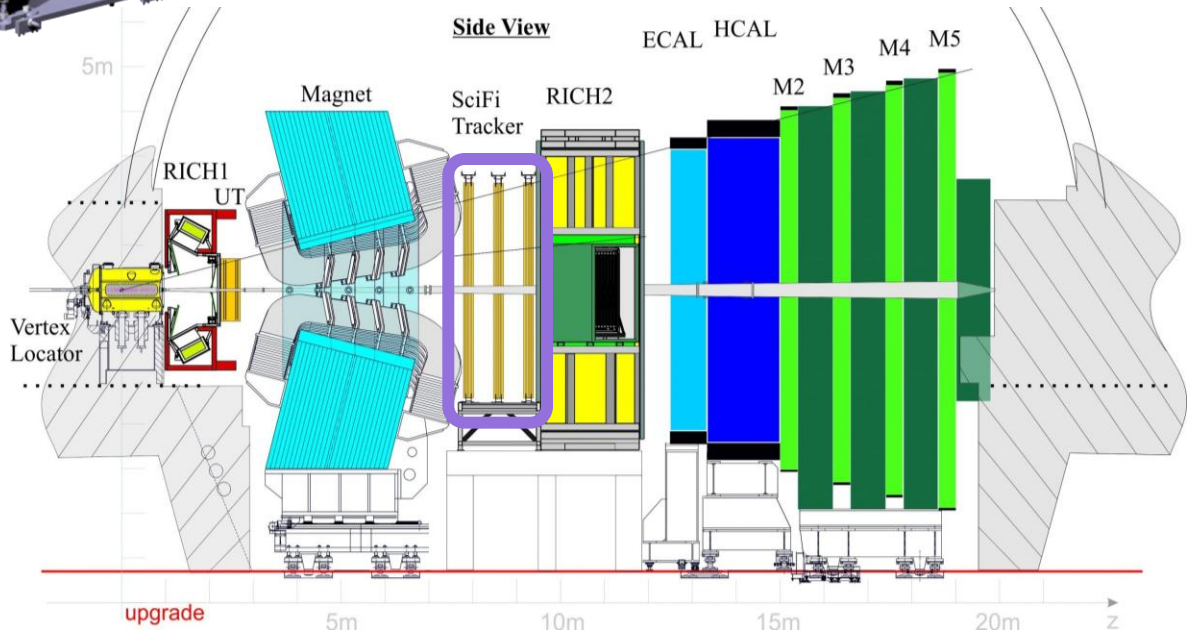
- This thesis focuses on the upgrade of **photodetectors for two forward physics detectors.**
- **FASER**: The **F**orw**A**rd **S**earch **E**xpe**R**iment at LHC.
- **480m away from ATLAS…**
  - Searching for **long lived, weakly interacting particles**.
- **Veto stations** to reject background.

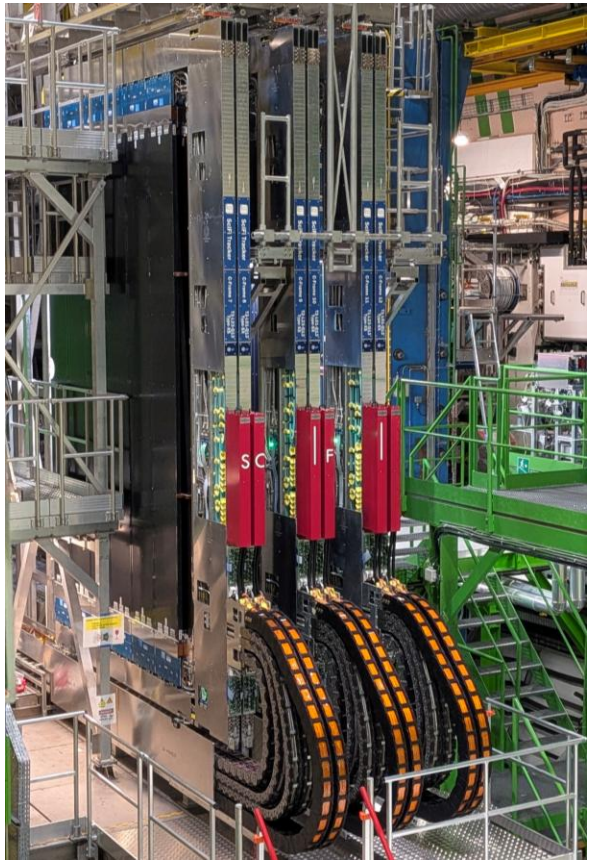




- **LHCb**: **LHC b**eauty experiment.
  - Heavy flavour physics.
- **SciFi: Sci**ntillating **Fi**bre **Tracker**.
  - Downstream tracker.
- **12 tracking layers.**
  - **340 m² of Ø250 µm fibres.**



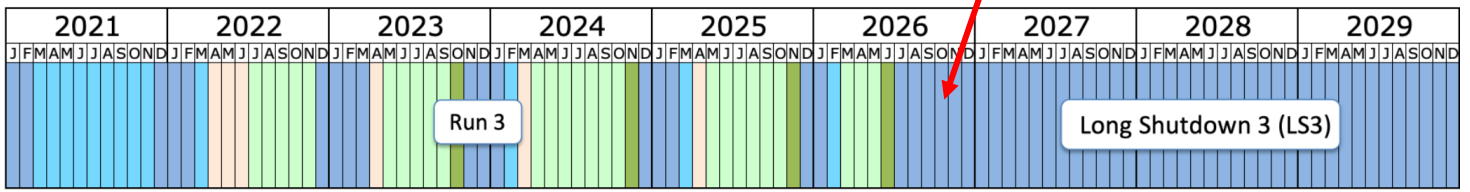




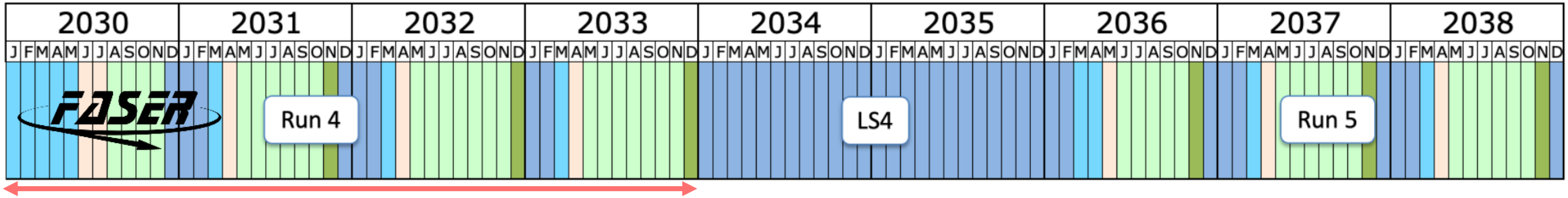
Preparation for High Lumi LHC

- **The detectors at the LHC will need to adapt to the higher occupancy and radiation fluence.**
  - **FASER will be upgraded for Run 4.**
  - **Cooling for LHCb SciFi will be upgraded Run 4.**
  - **LHCb will be upgraded for Run 5.**

LHC:



HL-LHC:



FASER Upgrade:

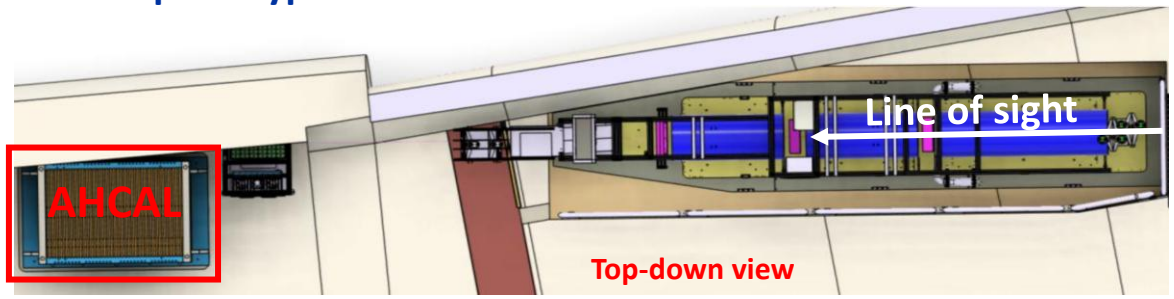
Why? The emulsion detector FASERν will collect limited data, upgrade to study TeV neutrinos and further BSM searches at HL-LHC.

Upgrade:

- **Additional electronic neutrino detectors.**
  - **Veto station for off-axis detector.**
- **Replacement of existing veto stations.**
  - FASER veto stations will use wavelength shifting bars.
  - FASERν veto station will have a larger area.

Prototype Veto Scintillator Detectors

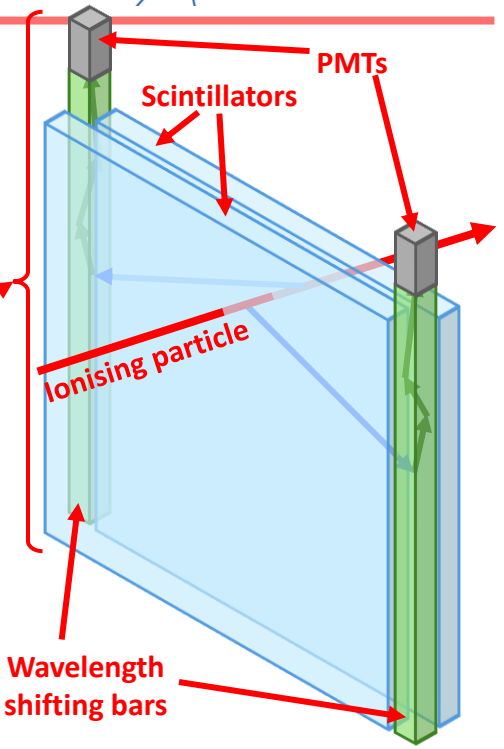
- The AHCAL is a prototype for the off-axis neutrino detector.
  - 40 layers of passive (iron) and active layers made of many 4x4 cm² scintillator tiles.
- **Two prototype veto scintillator detectors were made at CERN.**

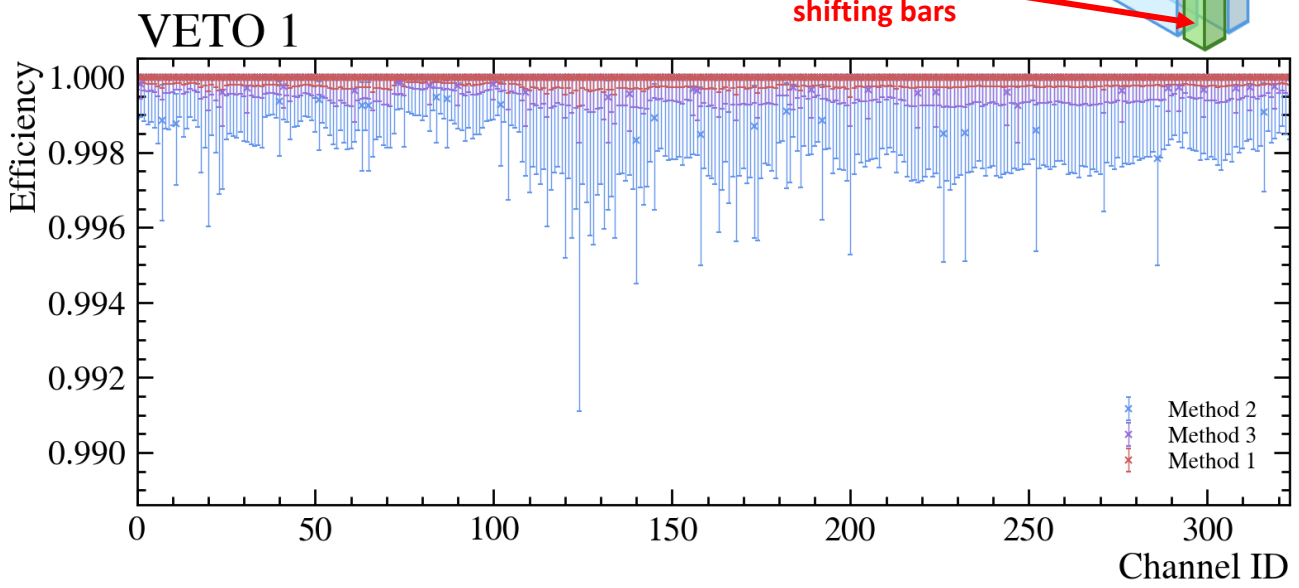


QUESTION: Can we make a large-area, single tile, scintillator detector that is suitably efficient for a veto?

- **Yes**, two 80x80 cm² prototype vetoes were tested and installed in front the of AHCAL prototype.
  - Sufficiently high light yield in the areas furthest from the wavelength shifting bar.
  - The **efficiency of each veto scintillator is 99.9998$\pm^{0.0002}_{0.0006}$ %** (using muons from the ATLAS IP).
  - The updated light collection with a wavelength shifting bar was shown to be successful for large-area scintillators.



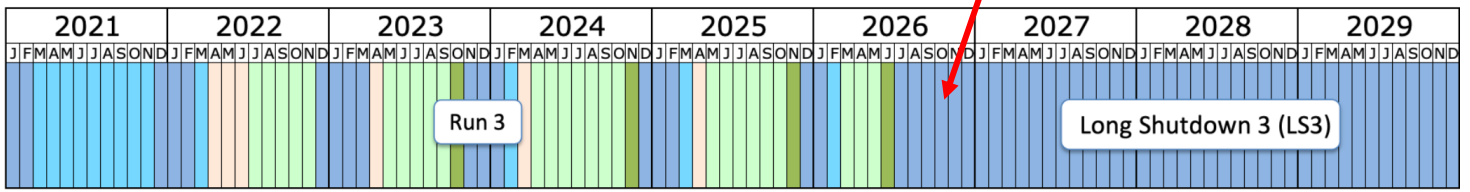




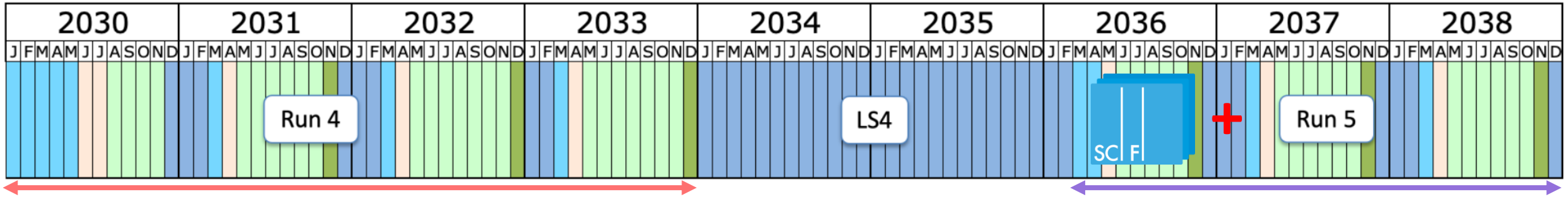
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  - **LHCb will be upgraded for Run 5.**

LHC:



HL-LHC:



FASER Upgrade:

Why? The emulsion detector FASERν will collect limited data, upgrade to study TeV neutrinos and further BSM searches at HL-LHC.

Upgrade:

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Scintillating Fibre R&D for HL-LHC:

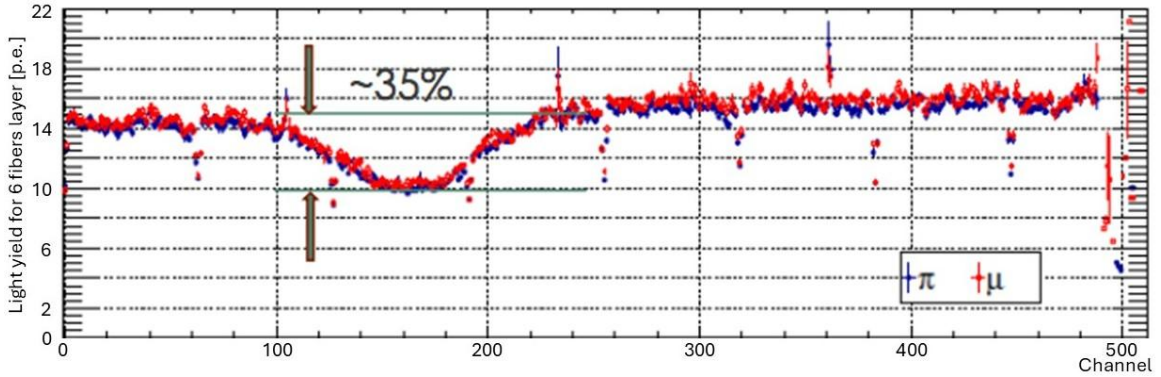
Why? To maintain the detection efficiency at the end of HL-LHC, radiation hard fibres with a high light yield are required.

Aim:

- Investigate a new radiation hard fibre candidate.
- Study of the effect of **coated, thin scintillating fibres** to increase the effective light yield.

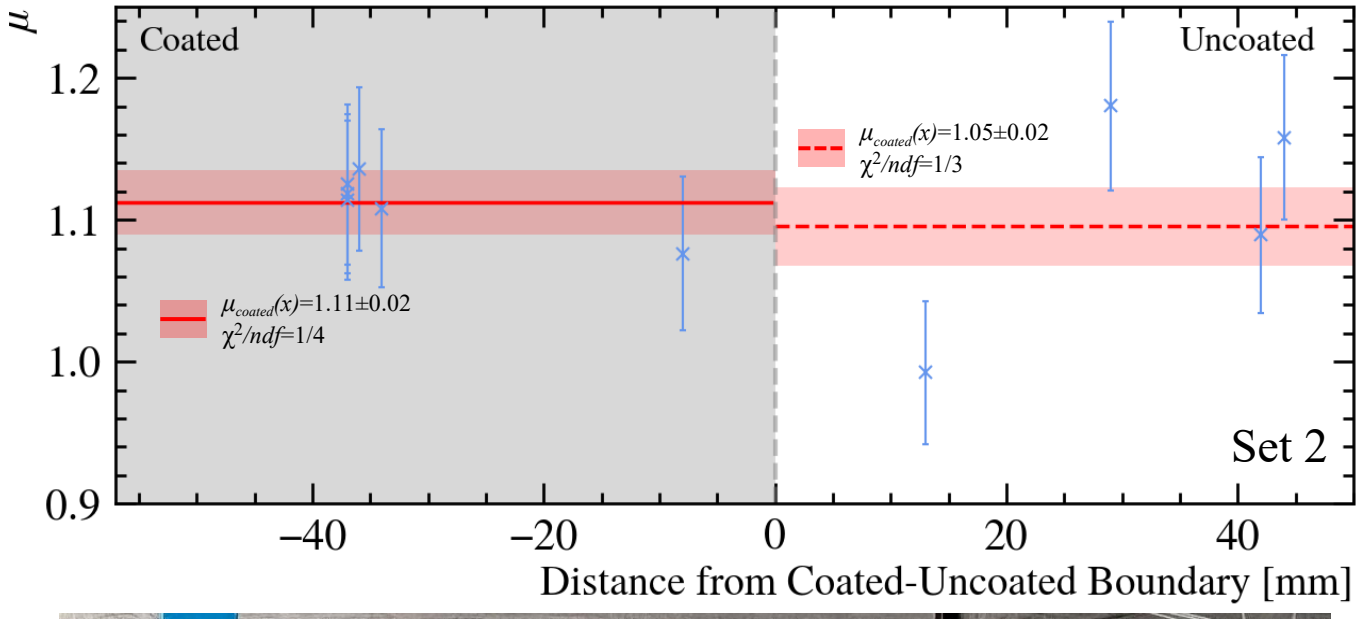
UV Reflective Coating for Thin Scintillating Fibres

- **Scintillating fibres are not completely radiation hard.**
  - **Scintillating fibres** are damaged when irradiated, becoming increasingly opaque.
- For **LHCb SciFi**, at the end of Run 4, there will be an estimated **35 % drop in the amount of light collected at the SiPMs**.
  - Before irradiation SciFi detects ~3 to 4 p.e. per channel.

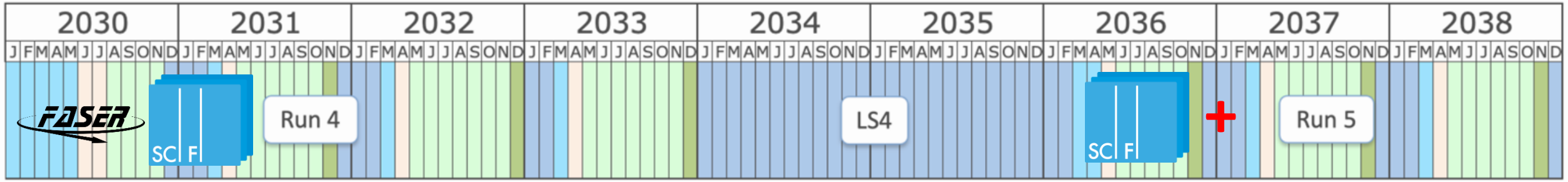


QUESTION: Can a thin, UV reflective coating improve the fraction of primary scintillation light that is wavelength shifted?

- Used aluminium as it was used previously to **reduced optical crosstalk** and (in theory) may also improve the light yield.
- For this campaign we used **round, double-cladded, Ø250 µm Kuraray SCSF-78MJ** fibres, from the LHCb SciFi Tracker:
  - Primary UV scintillated light ~260nm.
  - WLS ~450nm.
- Not yet, there was **no significant positive effect on the light yield observed.**
  - Several issues causing large uncertainties that were potentially too large to see any effect.
    - The work to understand the variations and uncertainties is still ongoing.



Future Work



FASER Upgrade:

Why? The emulsion detector FASERv will collect limited data, upgrade to study TeV neutrinos and further BSM searches at HL-LHC.

TO FINISH:

1. The muon flux through the AHCAL.
2. A timing study.
3. A study of the gain response to the proximity of the dipole magnets used in FASER.

FUTURE CONTRIBUTIONS:

- **The details of future FASER work are still maturing** (subject to the on-going approval process)**.**
  - Design and construction of the scintillator-based detectors FASERCal or the on-axis detector for the Run 4 upgrade.

Scintillating Fibre R&D for HL-LHC:

Why? To maintain the detection efficiency at the end of HL-LHC, radiation hard fibres with a high light yield are required.

TO FINISH:

1. New alignment plates.
2. Switching from PMTs to SiPMs.
3. An isolation transformer will be installed.
4. Attenuation of UV through base material of fibres.

FUTURE CONTRIBUTIONS:

- Analysis for the irradiation study of a new radiation hard fibre candidate (Ø250 µm SCSFSDG-02 and SCSF78-MJ as a reference) for the upgrade of LHCb SciFi for HL-LHC.

LHCb SciFi Cooling Upgrade:

Why? To maintain a useful SNR SciFi needs to be 10 °C **colder** for **Run 4.**

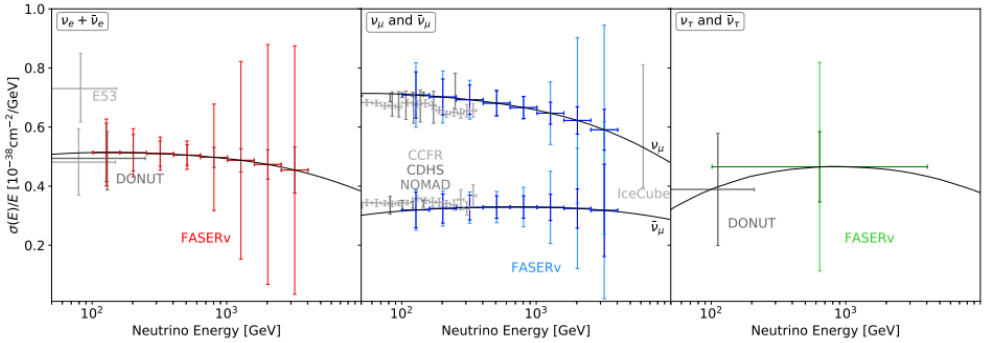
FUTURE CONTRIBUTIONS:

- Performance of cooling and services during Run 3.
- Dedicated study to tune set points of services for Run 4 to run SciFi at a colder temperature.

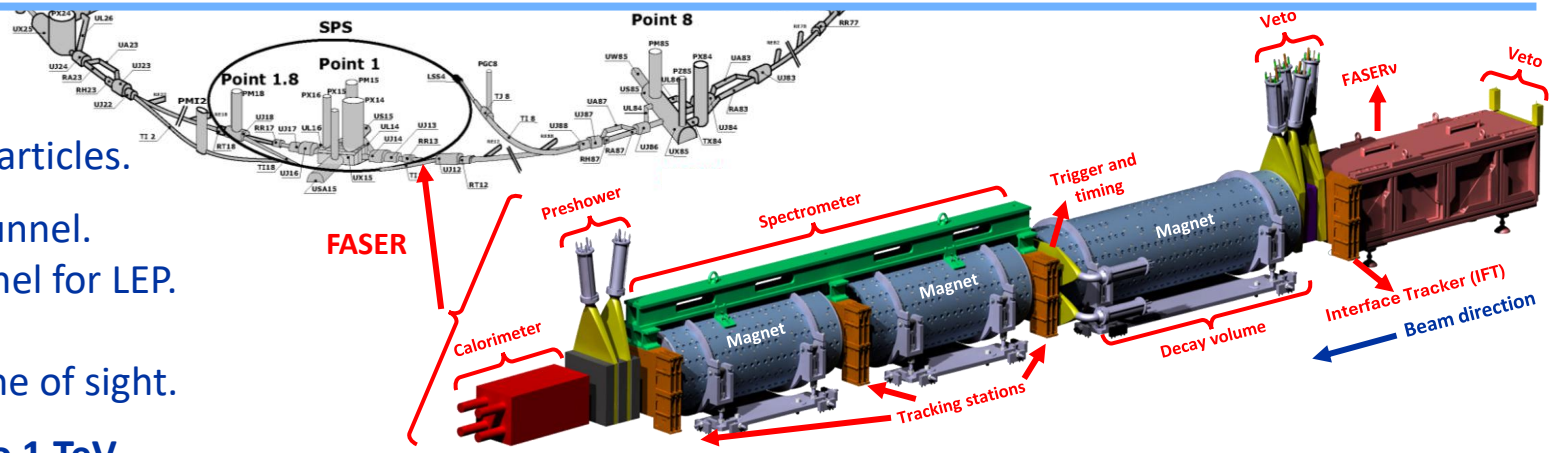
BACKUP

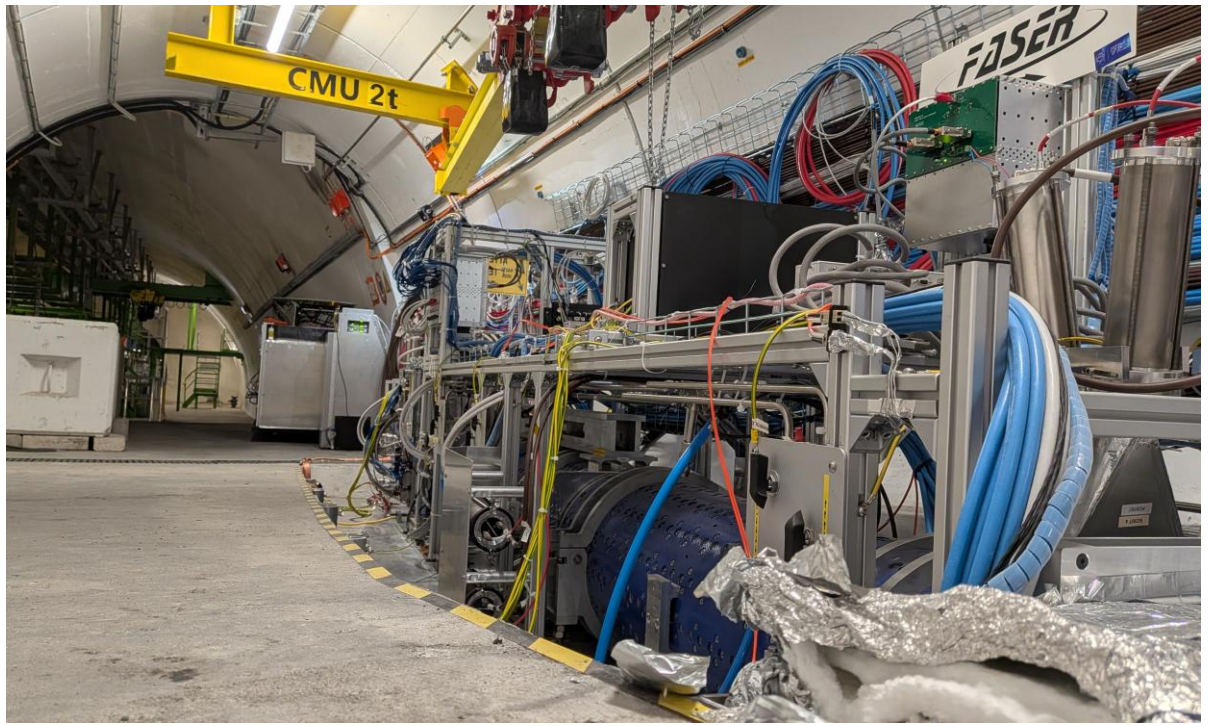
FASER Overview

- The **F**orw**A**rd **S**earch **E**xpe**R**iment at LHC:
  - Started data taking in **Run 3**.
  - Searching for light, very weakly interacting particles.
- Sits between 480m away from ATLAS in the LHC tunnel.
  - Just after the LHC LSS in an old injection tunnel for LEP.
  - **On the line of sight from IP1**.
  - **100m of rock** shielding the position of the line of sight.
- FASER explores neutrino energies from **600 GeV to 1 TeV**.
  - Measurements of **neutrino cross-sections for unexplored energy ranges.**



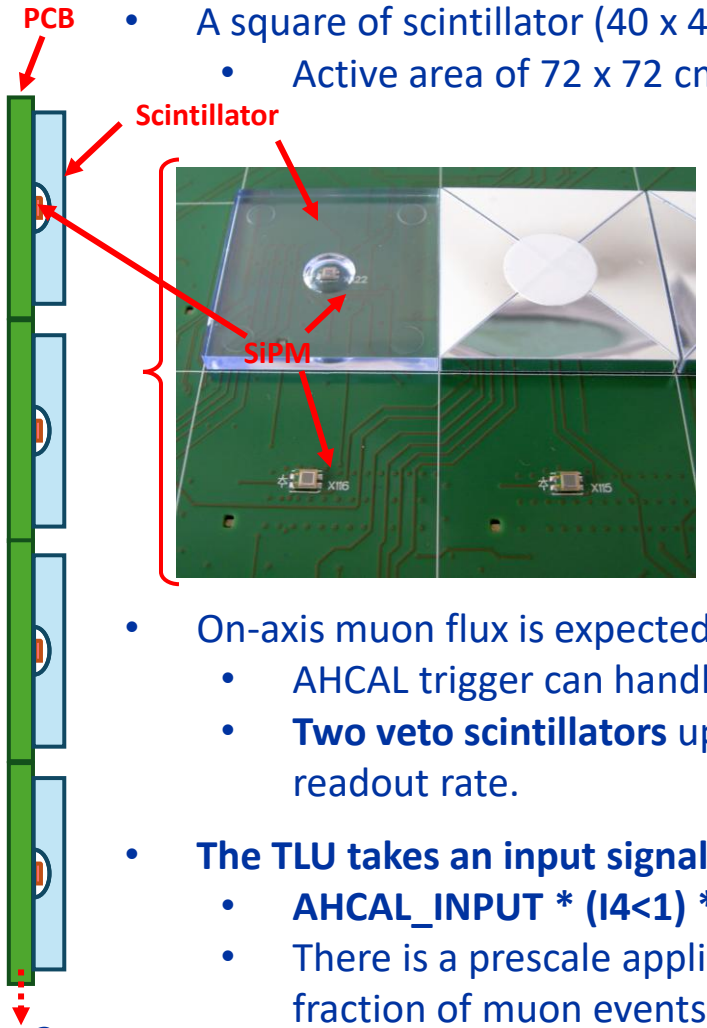
- Two prototype calorimeters were installed during the 2025/26 YETS to test a proposal for an off-axis electronic neutrino detector for a planned upgrade during LS3.
  - For neutrino physics we have **FASERν**.
    - For HL-LHC there will be **limited or no operation**.
    - Therefore, we **need a new neutrino detector**.





AHCAL Overview

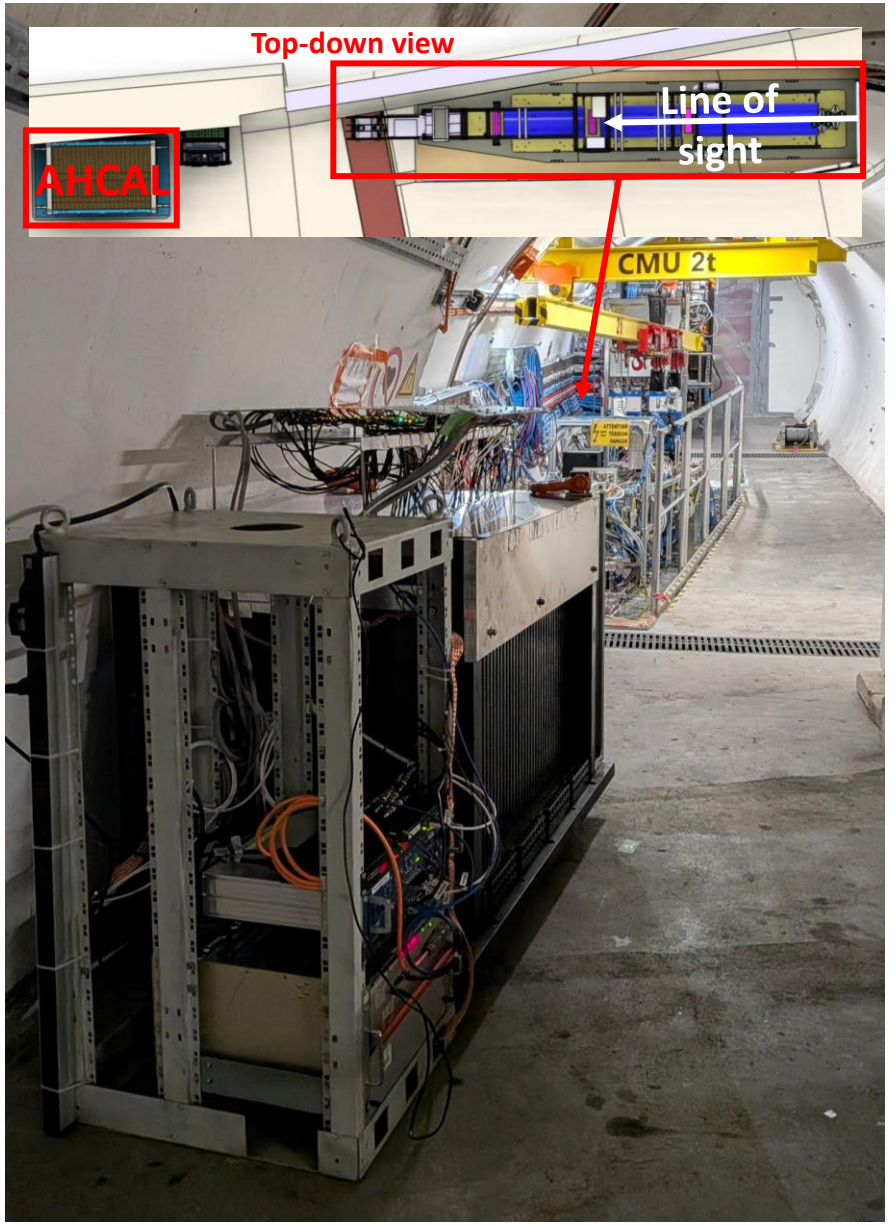
- The **AHCAL prototype** is an off-axis, **stand alone neutrino detector.**
  - **40 layers** of passive (iron) and active layers.
- **A module** (720 x 720 mm) has 9 SPIROC ASICs.
  - Each ASIC has 36 channels.
  - A square of scintillator (40 x 40 x 3mm) covers every SiPM.
    - Active area of 72 x 72 cm with 324 organic scintillators per module.



- **4 layers are used as trigger layers.**
- To trigger the AHCAL, a coincidence of 2 out of 4 trigger layers is required.
- A Trigger Logic Unit (TLU) is passed 4 inputs (I0, I1, I2, and I3) from the AHCAL.
  - **(I0+I1+I2+I3) > 1**

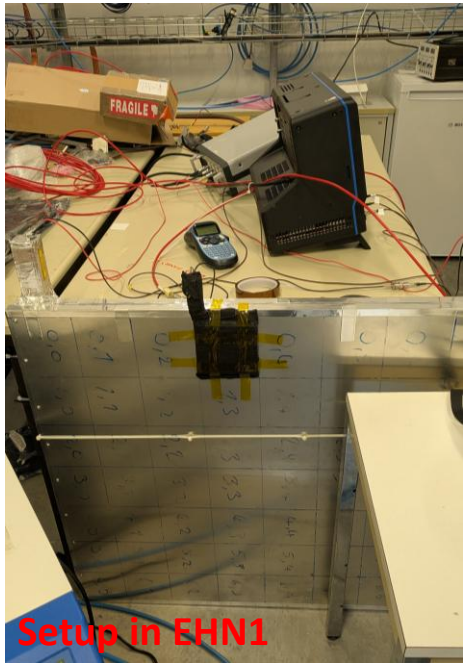
- On-axis muon flux is expected to be 0.4 Hz/cm².
  - AHCAL trigger can handle < 1 kHz which is therefore not sufficient.
  - **Two veto scintillators** upstream of the AHCAL are used to reduce the readout rate.

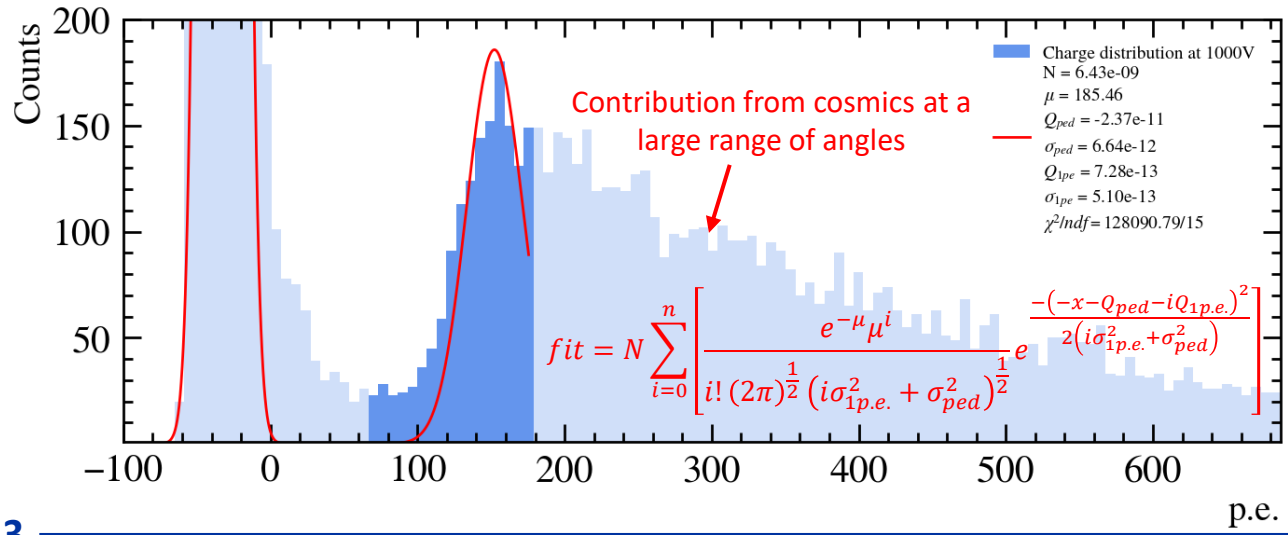
- **The TLU takes an input signal from each veto (I4 and I5).**
  - **AHCAL_INPUT * (I4<1) * (I5<1) > 0**
  - There is a prescale applied to the logic for the veto inputs to store a fraction of muon events.

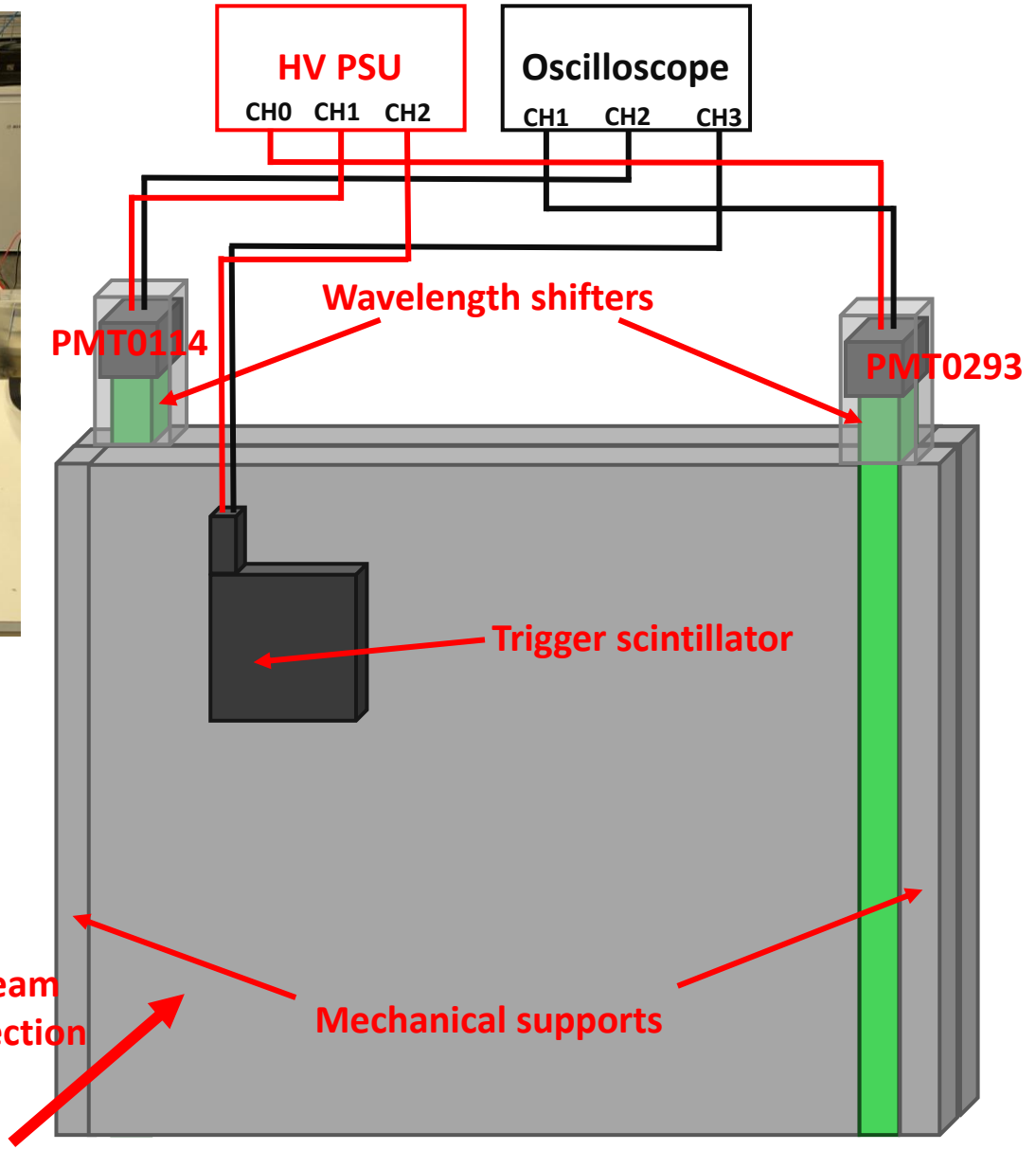


Setup

- 2 80x80 cm scintillators at 90° to the floor
- Small 10x10 cm trigger scintillator
- Data taken with the trigger scintillator at different positions to measure the difference in light yield over the veto scintillators.
- PMT0114 was taken from the tunnel
  - $G_{PMT0114} = 10.2\times10^6 \pm 0.1\times10^6$
- PMT0293 is new
  - $G_{PMT0293} = 4.0\times10^6 \pm 0.2\times10^6$
- The pedestal fitted with a Gaussian distribution
- Signal peak fitted using the fitted pedestal and the previously fitted single photoelectron peak



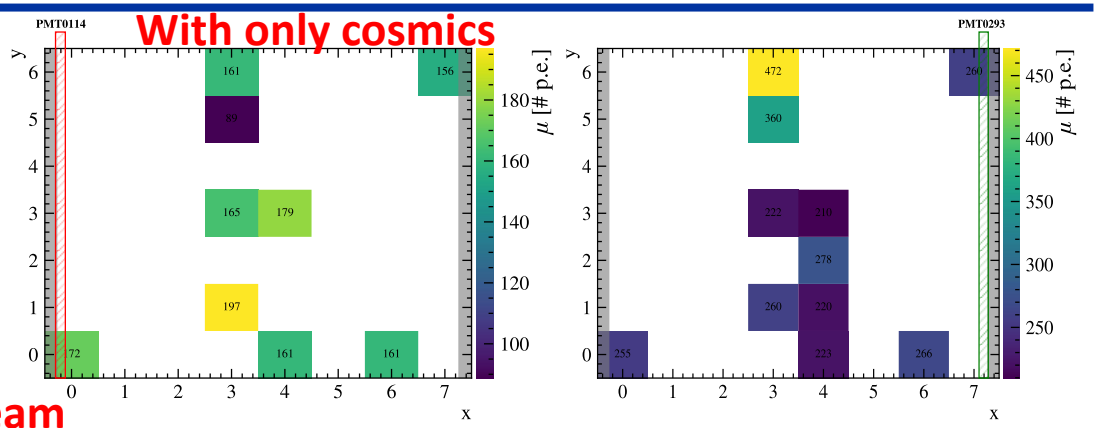




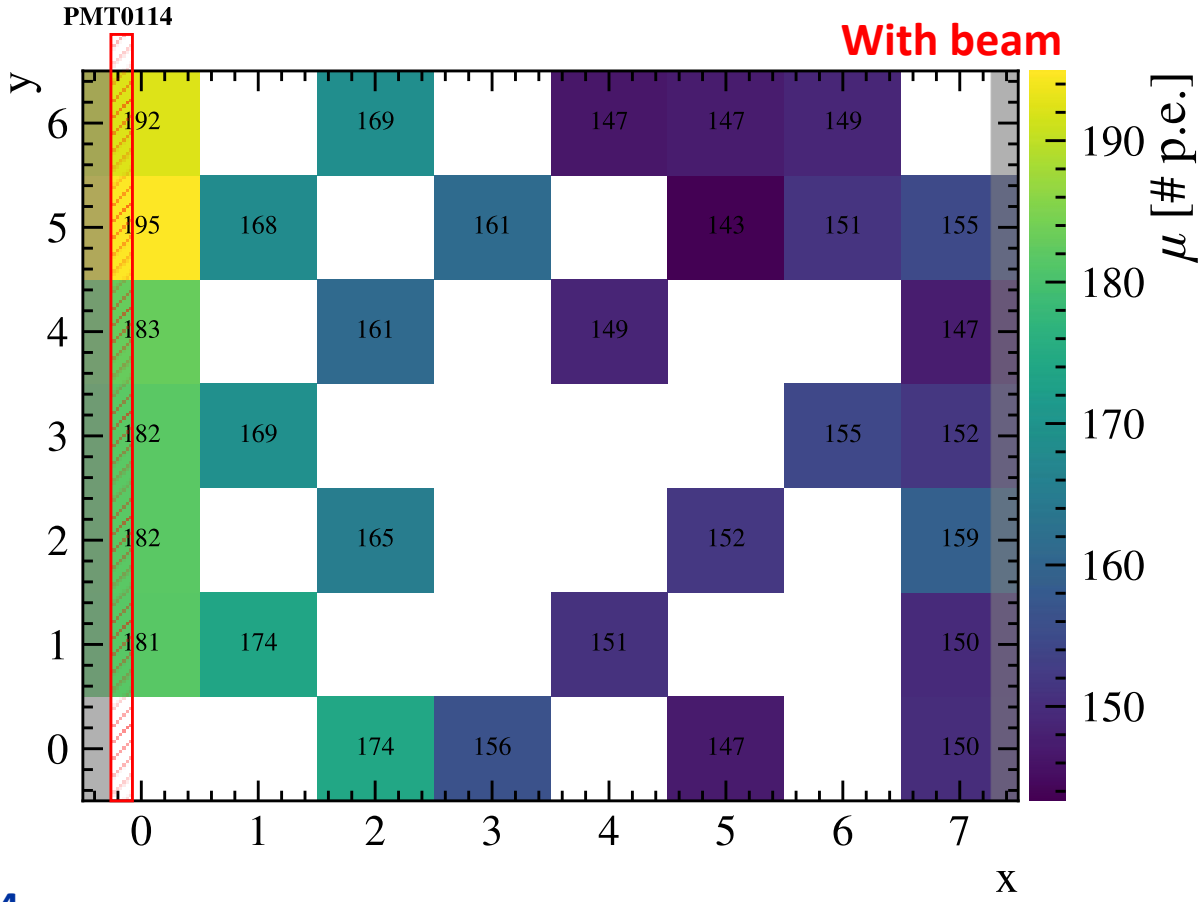
LY: Beam vs Cosmics

- Scintillators are 90° to the floor, the area facing upwards (2x80 cm) is << than the area facing the beam (80x80 cm)
  - Signals from cosmics have a large smear due to the range of angles
  - As expected, the cosmics have a larger signal
  - Clear increase in LY as we approach the wavelength shifter

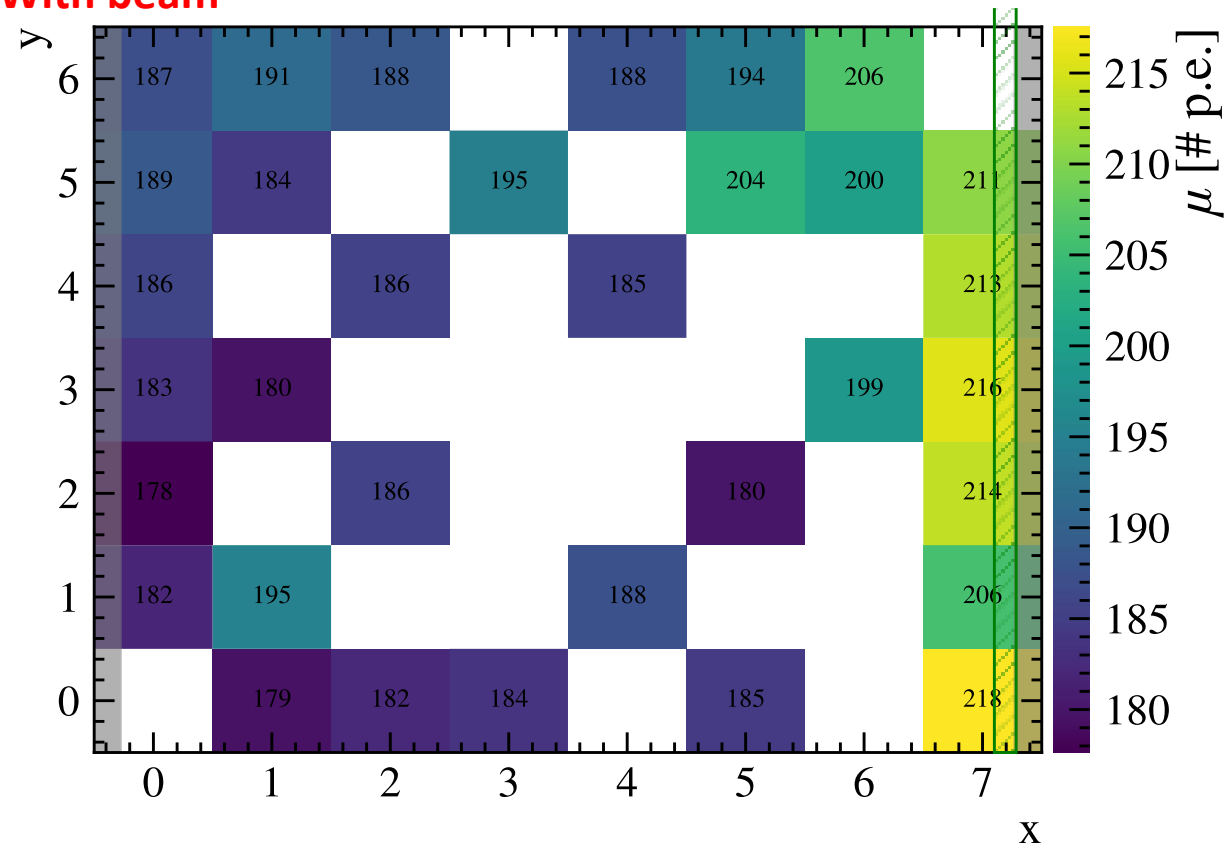
With only cosmics



With beam

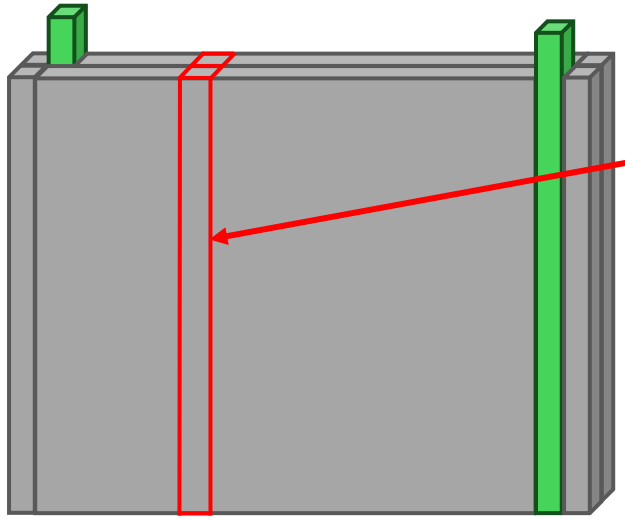


With beam



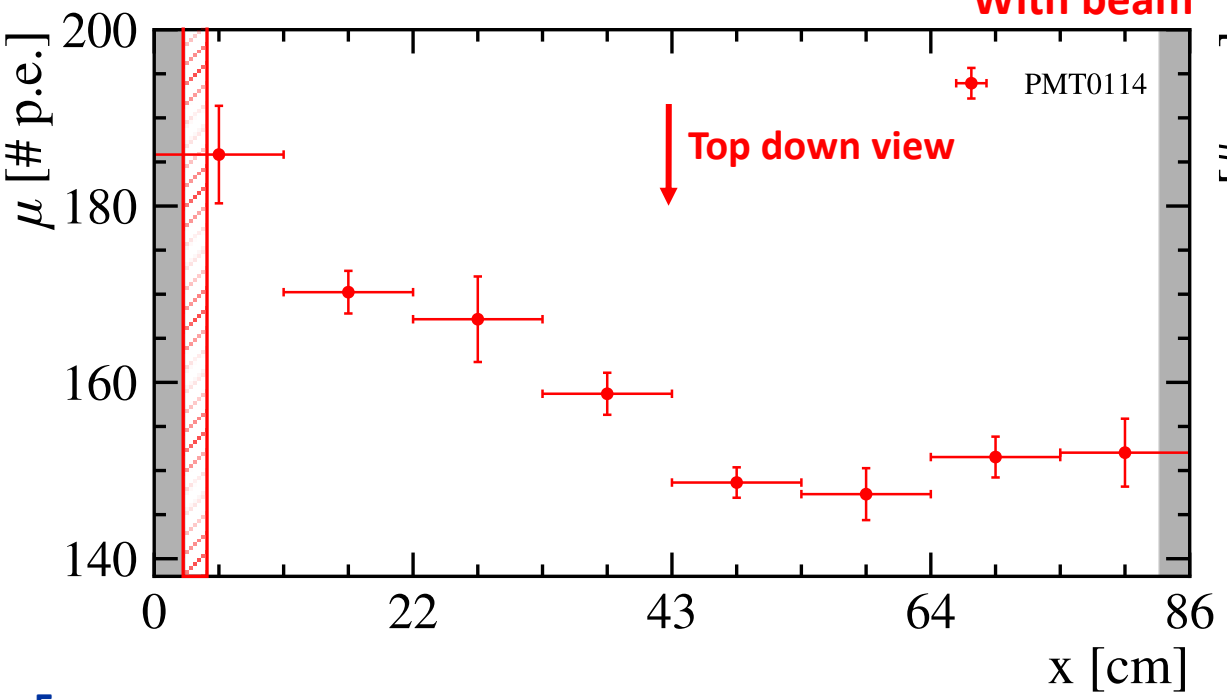
LY as a function of x position from the WLS

- Taking the average of the measurements taken at each x position shows the distance dependence of the light yield.
  - This was done only with measurements with beam.
  - The uncertainty in the signal average is the standard deviation of the measurements at each x position.
  - The uncertainty in x is the width of the trigger scintillator.

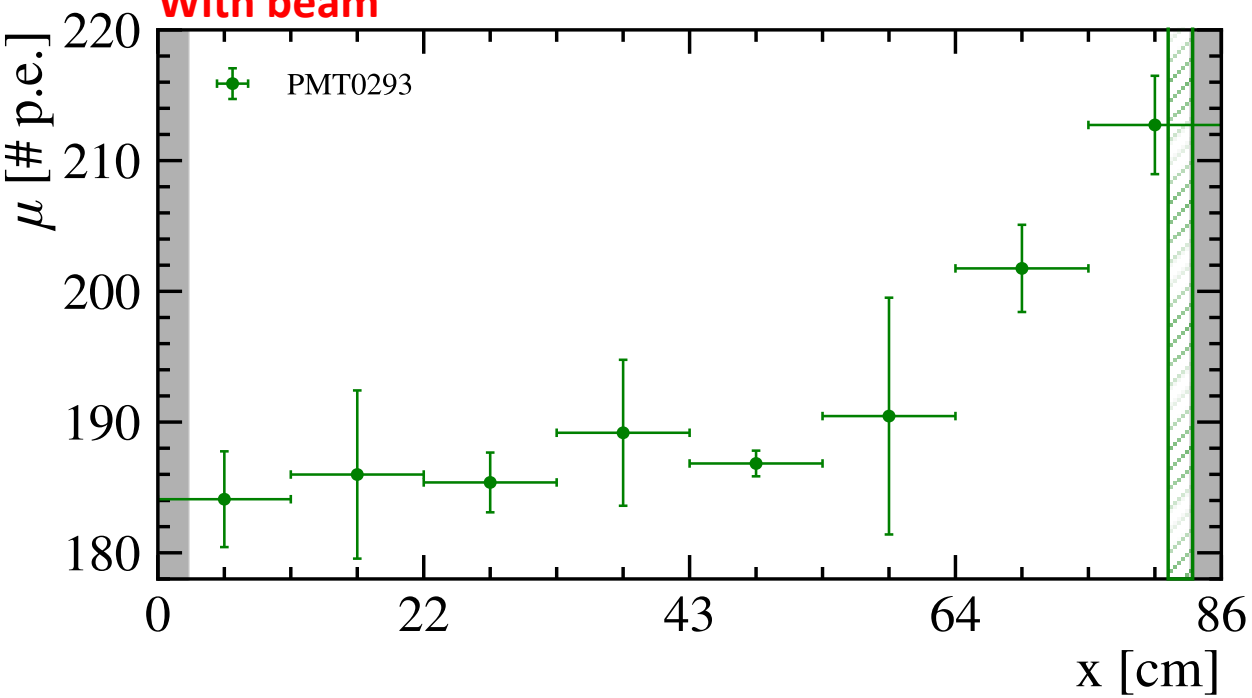


Average the signal along the y positions of the trigger scintillator for all steps in x

With beam



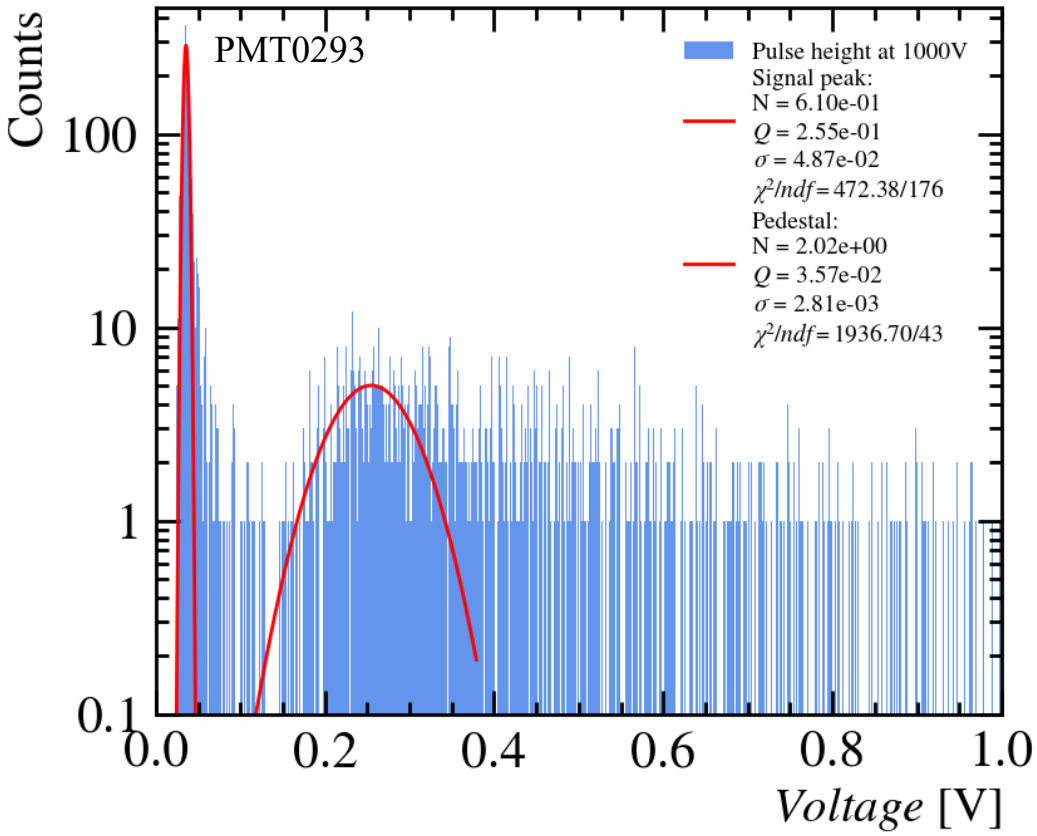
With beam



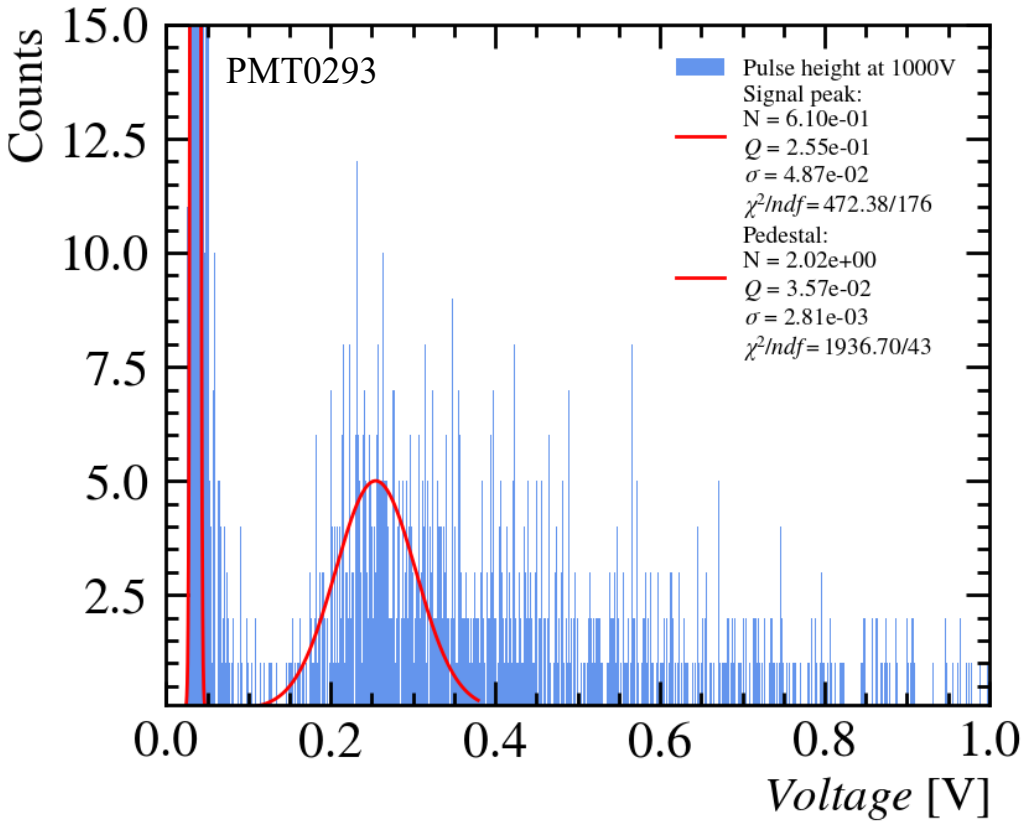
Pulse Height and Veto Efficiency

- The pulse height was measured at a few positions across the veto scintillators.
  - The pedestal was fitted and removed from the total area and the efficiency of the PMT was calculated using the following:

$$eff = \frac{area\ of\ signal\ peak}{total\ area}$$



- To find where to integrate between for the pedestal and signal peak, the data was fitted.
  - As before, the pedestal was fitted with a Gaussian distribution.
  - The signal peak was fitted with a Gaussian distribution.
    - The leading edge of the signal distribution is considered due to smearing from muons with a large range of angles.
- The area of the pedestal was removed from the area considered as the additional pedestal is due to the trigger.



Pulse Height and Veto Efficiency

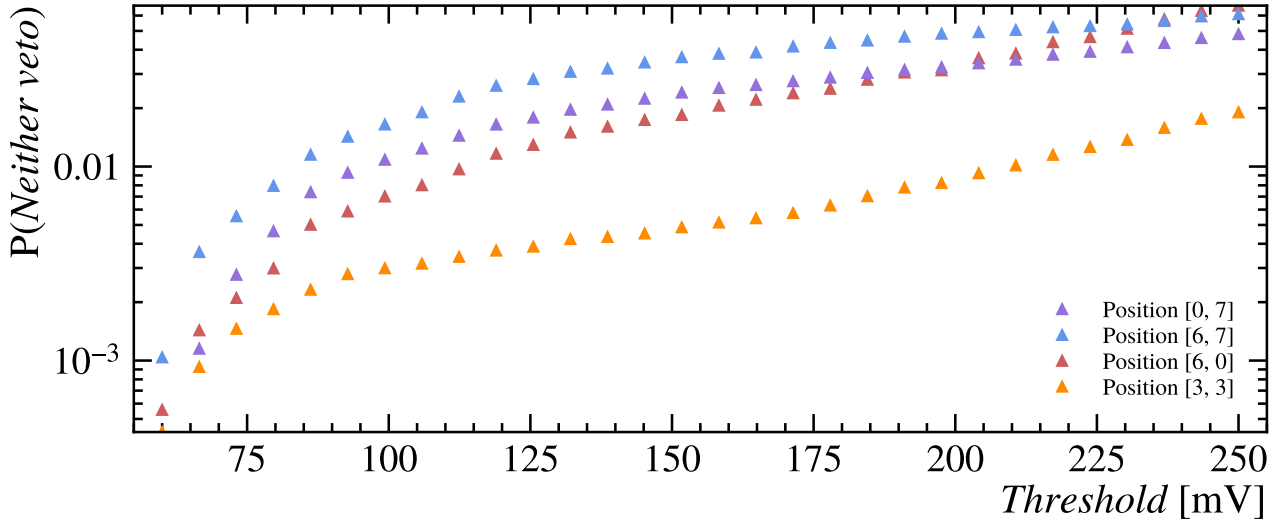
- To find the vetoing efficiency of each scintillator, different thresholds were set from 60mV through to 250mV in steps of 5mV.

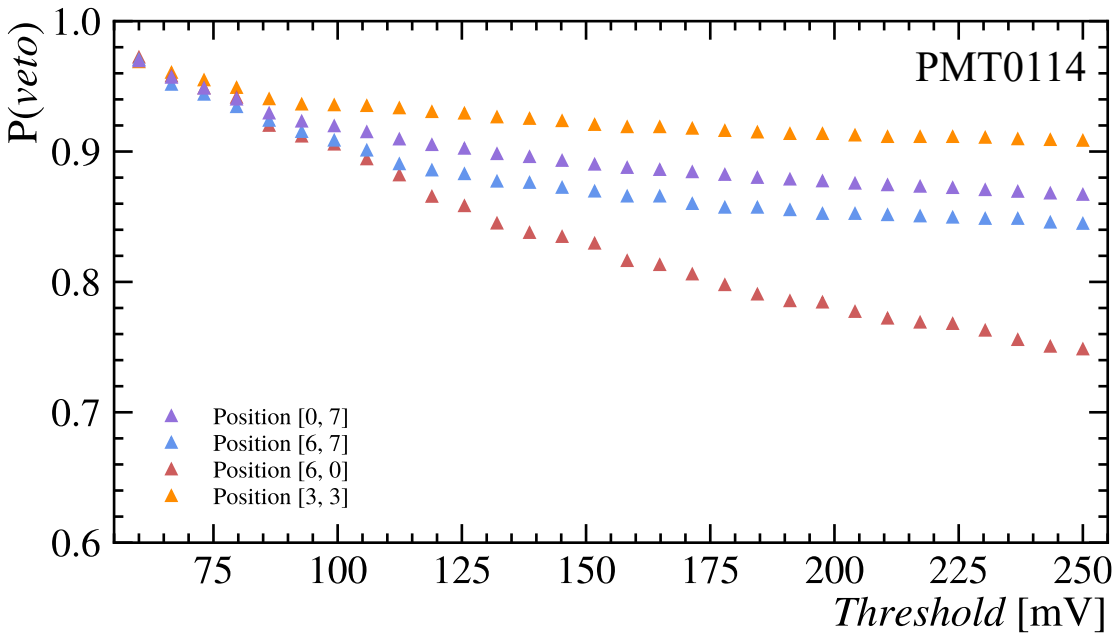
$$eff = \frac{area\ above\ threshold}{total\ area}$$

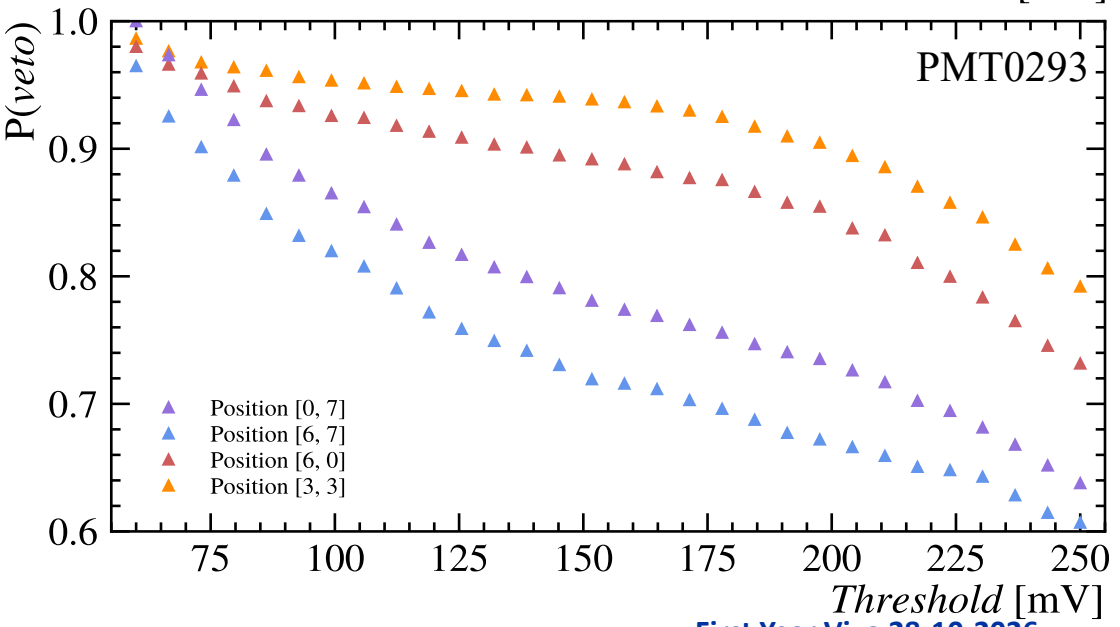
- PMT0114 has a larger separation between the pedestal and the signal peak in addition to less noise than PMT0293 => the efficiency does not decrease as quickly.
- Combining this for the two scintillators gives us the probability that neither of the scintillators veto an incident particle.

$$P(Neither\ trigger) = (1 - eff_{PMT0114}) \cdot (1 - eff_{PMT0293})$$

- Threshold < **85mV** would ensure a probability that either of the PMT's veto particles with > **99%** efficiency for particles incident at any position in the scintillator.

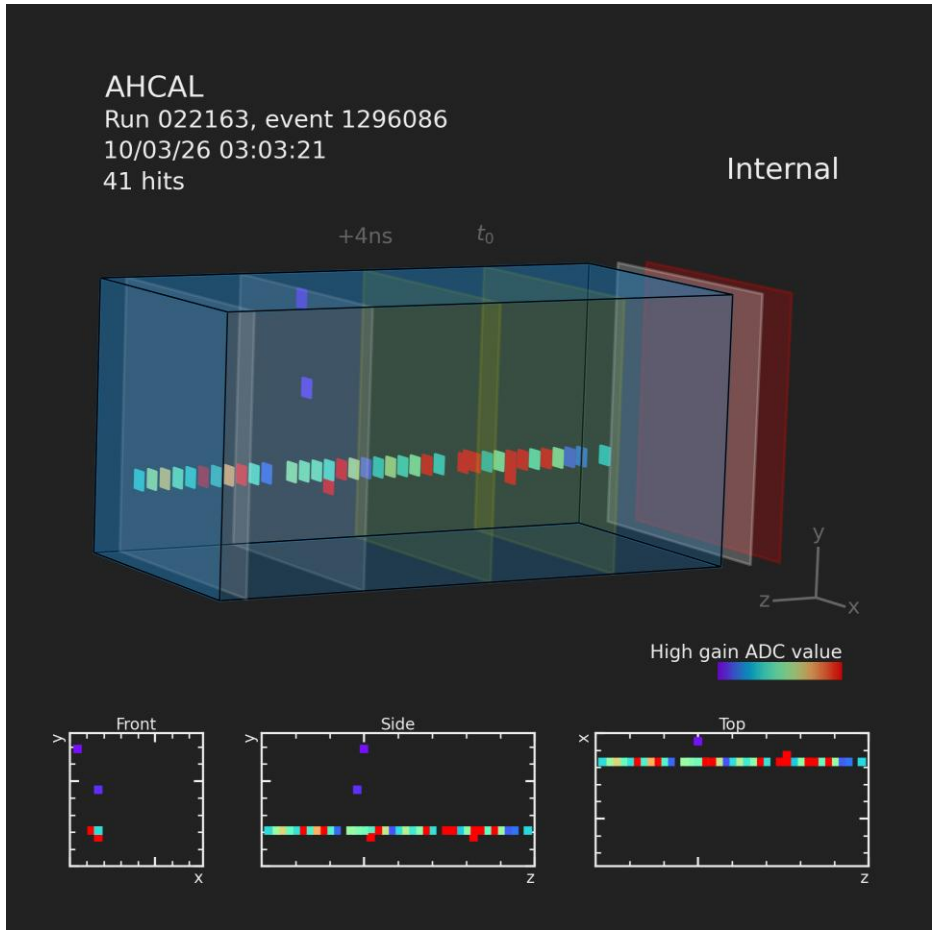






Muon Selection - Selected Cuts

1. **During stable beams**
2. **Maximum number of hits**
   - Maximum 10 noisy channels seen.
     - 34 working layers.
     - Cut on a maximum of 46 hits.
3. **Straight Track passing through a minimum number of layers.**
   - Ensures the track is a muon.
   - Require a straight track to make it simple to find the position it passed through the scintillators.
     - High rate of muons therefore should be no issue for the amount of statistics.
4. **Required front layers in a track**
   - It was seen for the lowest channels the track was rarely within the acceptance of the scintillator due to the angle of the AHCAL.
     - Requiring the track to pass through either of the two first working layers removes these tracks.
5. **Secondary track cut**
   - We need to require only one track to reduce the chance the position a muon passes through the scintillators is incorrect.
     - Required at least 3 consecutive hits in a neighbouring channel in the next layer.
     - Cut on maximum number of hits will cut longer tracks.



Veto Scintillator Efficiency - Methods

3 Methods:

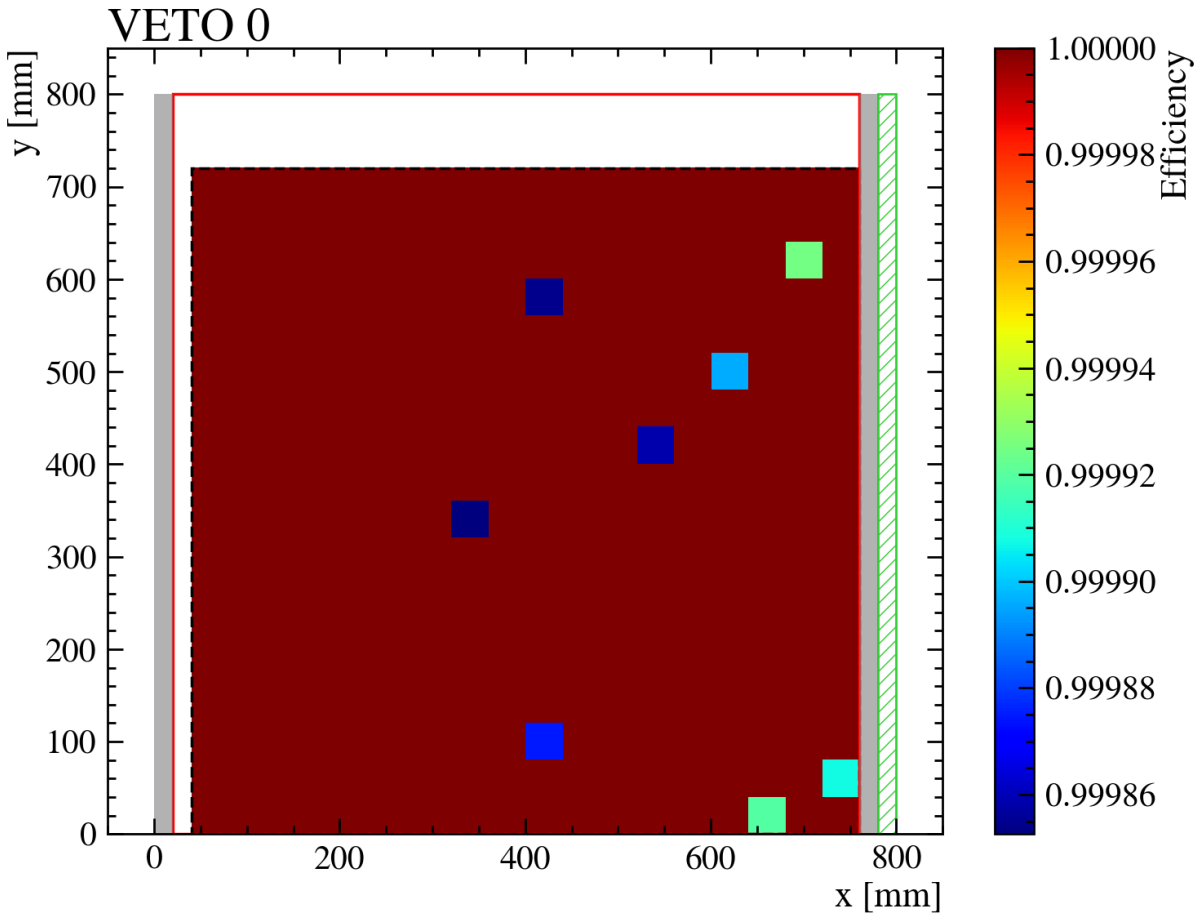
1. **Using Physics (AHCALPhysics_Veto_PreScale) runs during stable beams.**
   - (I0+I1+I2+I3>1) * (I4<1) * (I5<1) > 0
   - Verify a track is a muon by requiring the other scintillator is fired.
     - Can only use prescaled events -> require the other scintillator to have fired.

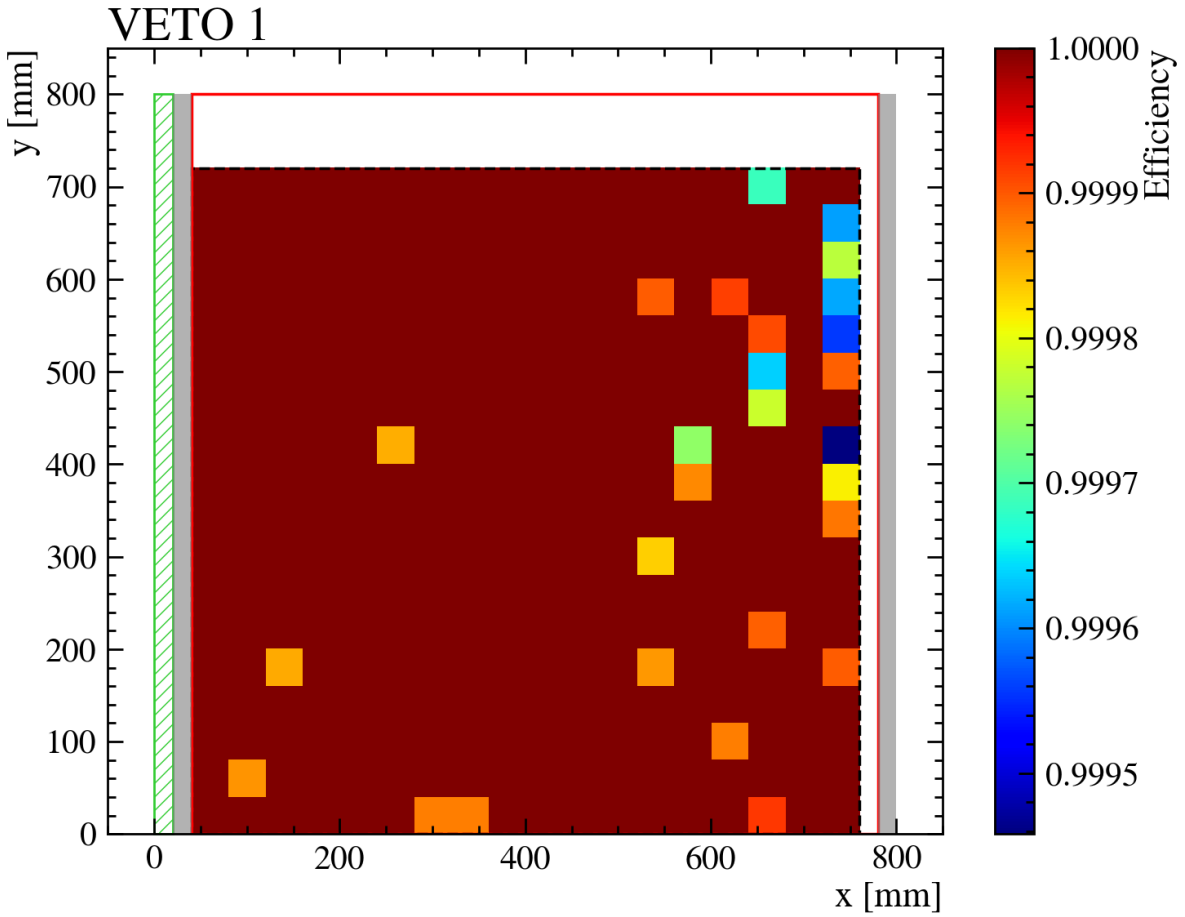
2. **Using two dedicated runs only triggering on the AHCAL.**
   - (I0+I1+I2+I3) > 1
   - Both trigger bits saved for the veto scintillators but not included in the trigger logic.
   - Only powering one scintillator at a time
     - PMT0293 OFF and PMT0114 ON
     - PMT0293 ON and PMT0114 OFF
   - Threshold for OFF PMT set to -1V to ensure no cross talk in the TLU.

3. **Using a run taken only triggering on the AHCAL with both scintillators ON.**
   - Runs 022854 and 022856 (AHCALPhysics_NoVeto)
   - (I0+I1+I2+I3) > 1
   - Taken during a low mu fill.
   - Both trigger bits saved for the veto scintillators but not included in the trigger logic.

Veto Scintillator Efficiency – Method 1

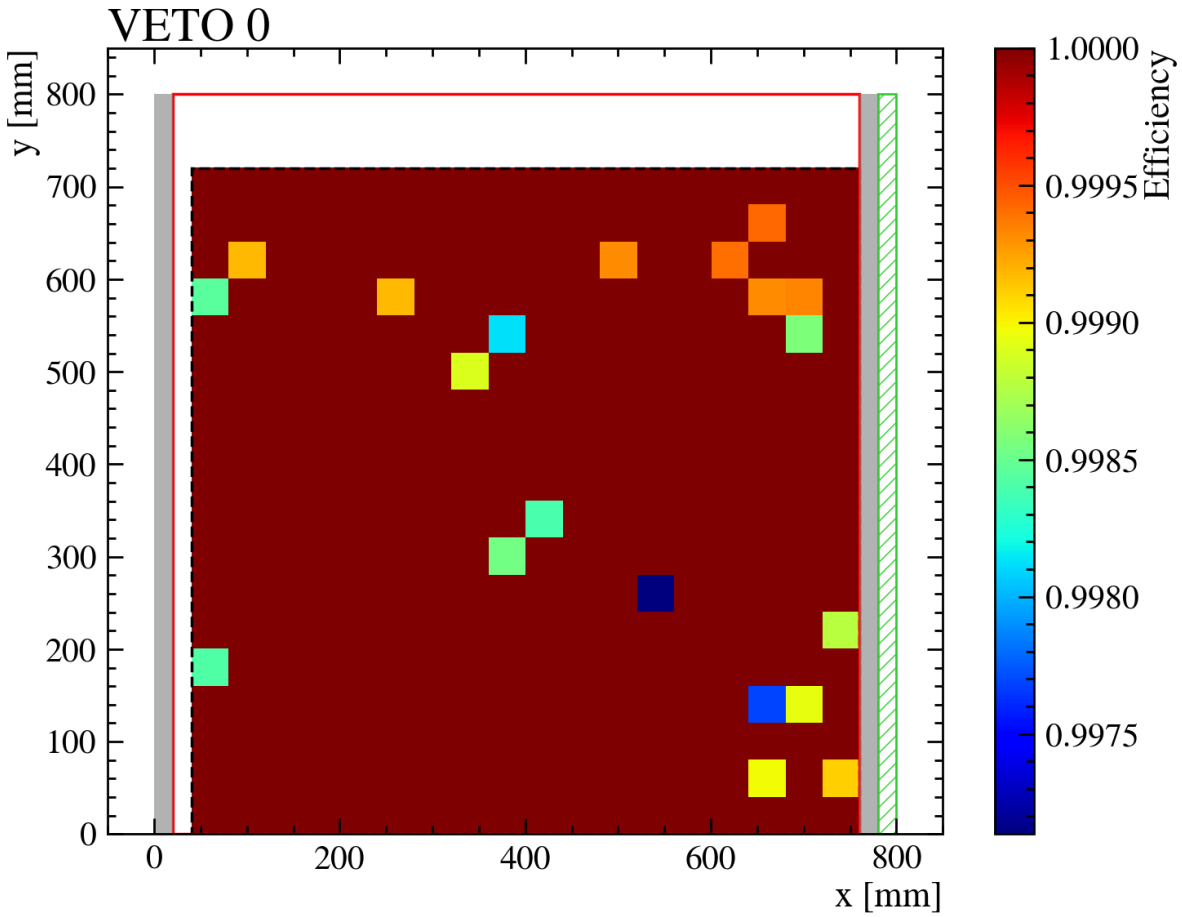
- **Method 1 uses physics runs:**
  - Very high efficiency **given the other scintillator fired** (> 99.9997 %).
  - But the statistics are limited by the strictness of the cuts.
    - Looser cuts might be okay as the required hit in the other scintillator additionally verifies an event is a muon.
  - **$\text{Efficiency}_{V0} = 99.9997^{+1.0822\times10^{4}}_{-1.5422\times10^{4}}\%$, $\text{Efficiency}_{V1} = 99.9998^{+2.6704\times10^{4}}_{-3.0900\times10^{4}}\%$**

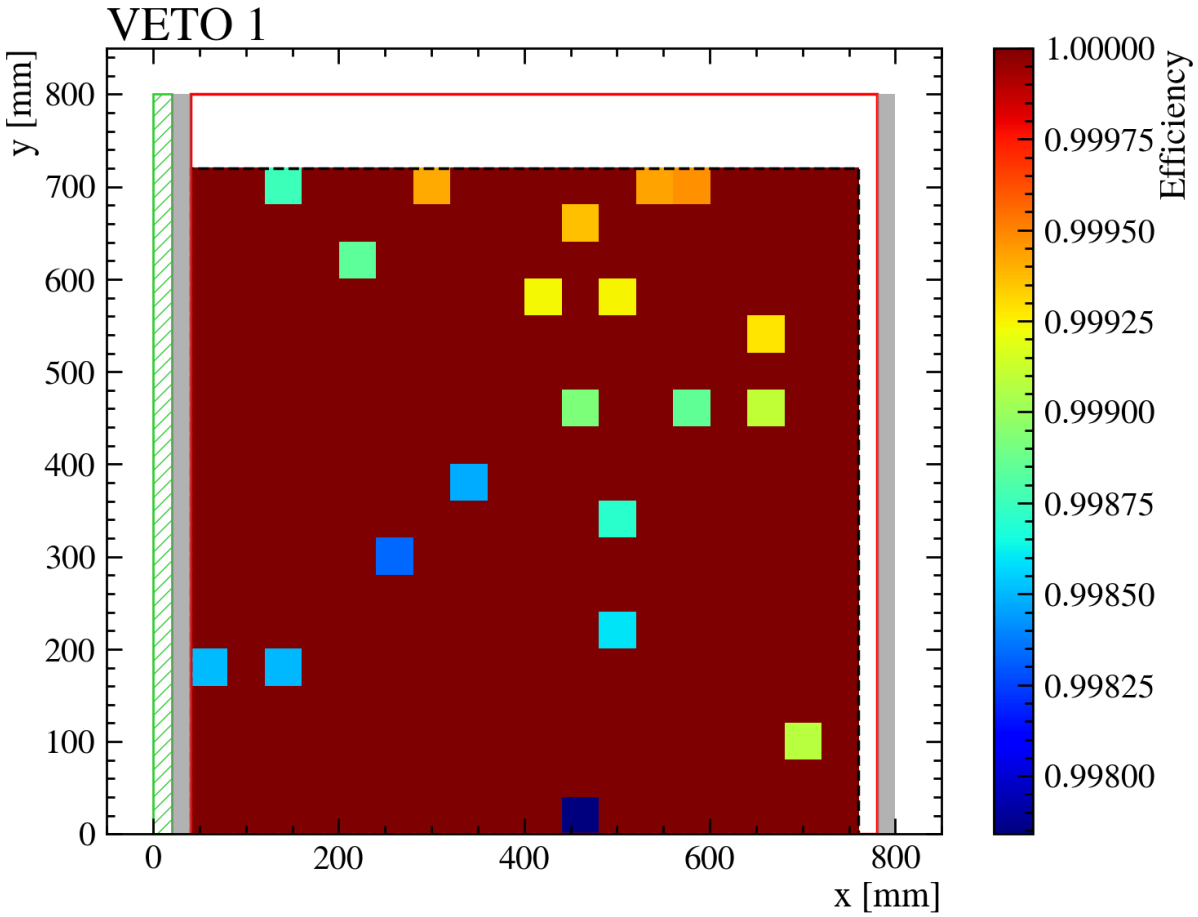




Veto Scintillator Efficiency – Method 2

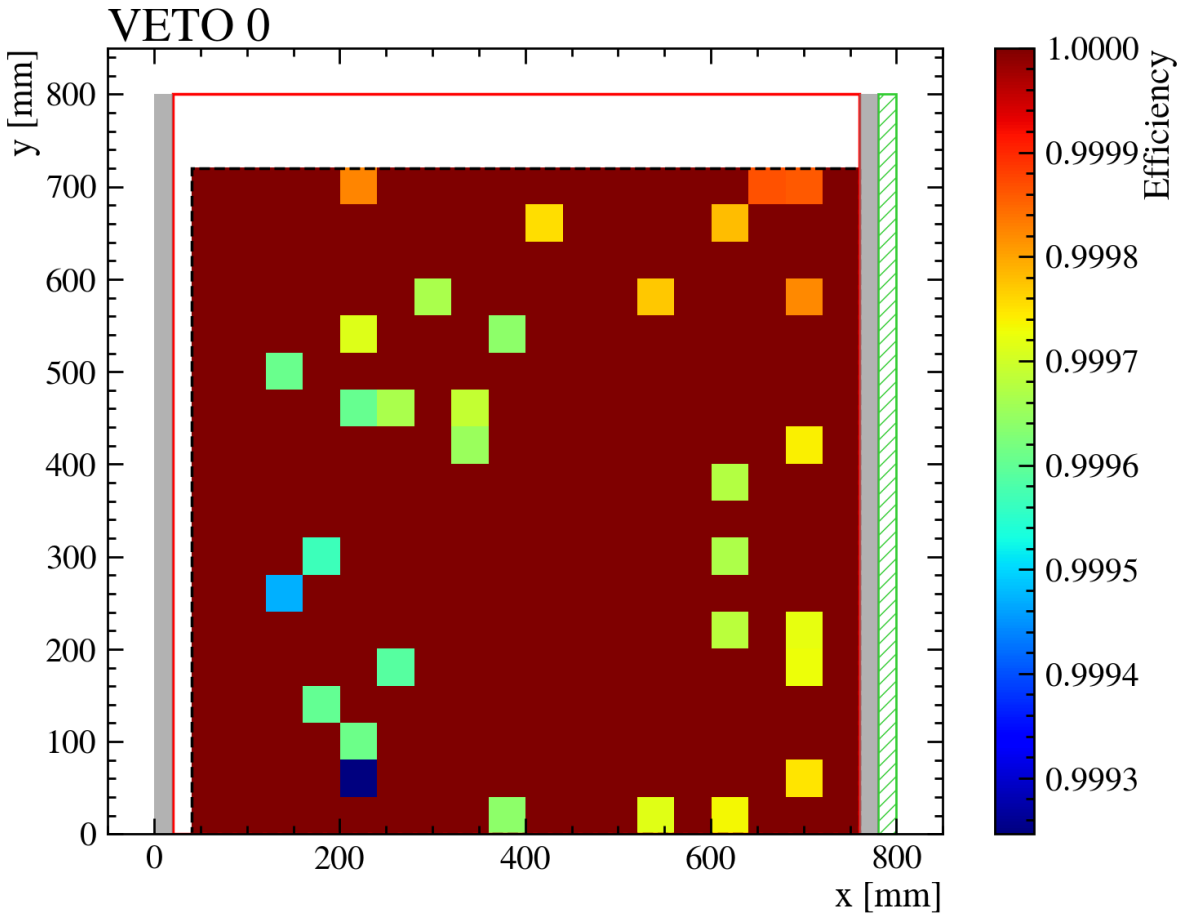
- **Method 2 uses dedicated runs triggering only on AHCAL:**
- Taken in one fill with 1740b fill at 6.8 TeV during MD4.
  - Much larger fraction of inefficient events compared to method 1.
- Only the HV for one PMT switched on at a time -> Completely independent.
- **$\text{Efficiency}_{V0} = 99.992^{+1.633\times10^{3}}_{-2.012\times10^{3}}\%$, $\text{Efficiency}_{V1} = 99.993^{+1.470\times10^{3}}_{-1.820\times10^{3}}\%$**

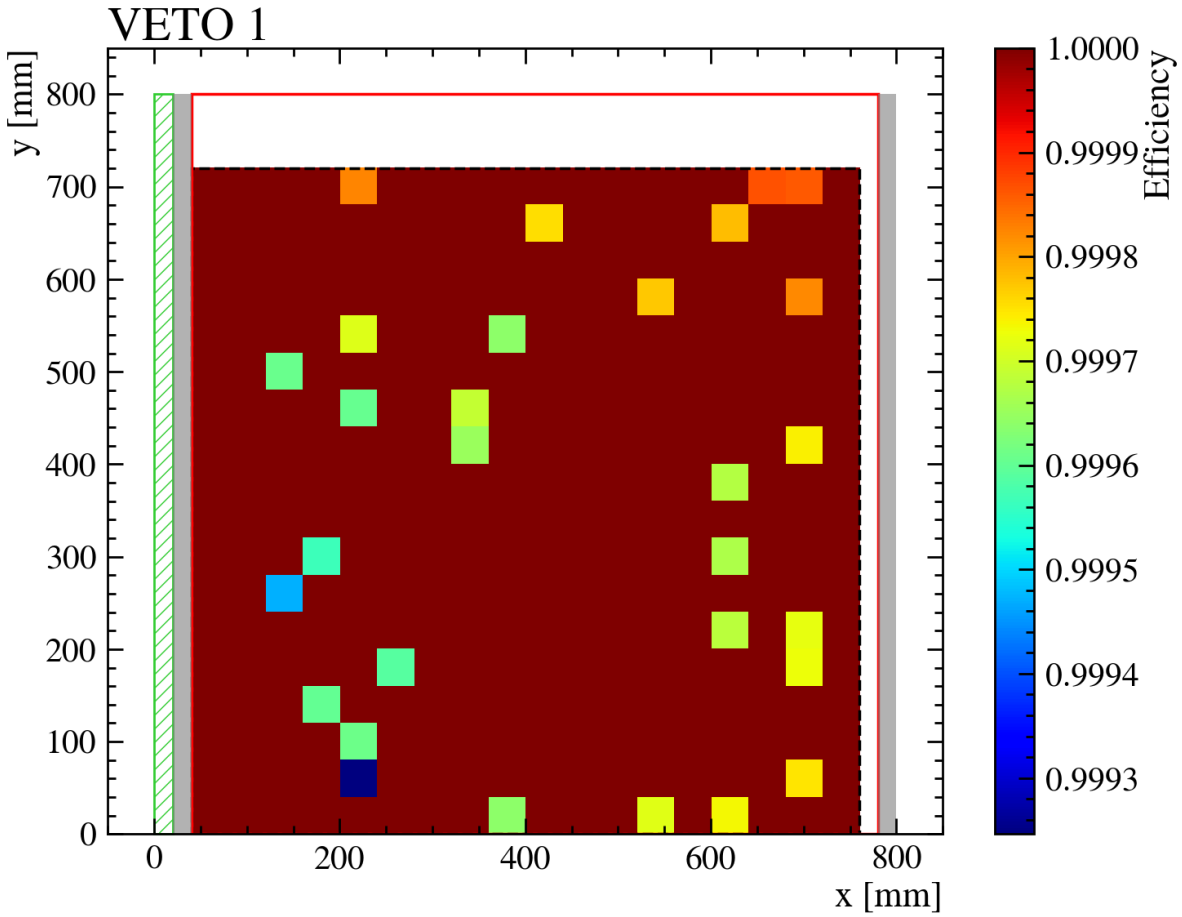




Veto Scintillator Efficiency – Method 3

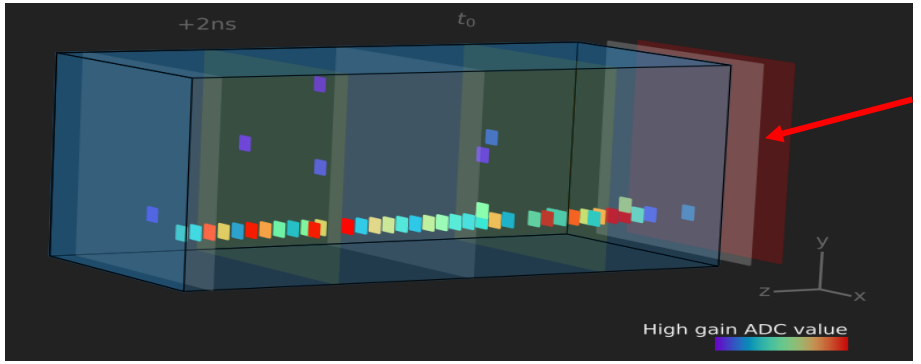
- **Method 3 uses a run triggering only on the AHCAL with HV for both scintillators ON.**
- **$\text{Efficiency}_{V0} = 99.997^{+5.337\times10^{4}}_{-6.370\times10^{4}}\%$, $\text{Efficiency}_{V1} = 99.997^{+5.166\times10^{4}}_{-6.201\times10^{4}}\%$**
  - Taken in two low-mu fills
  - Again, larger fraction of inefficient events compared to method 1.
  - **As we have both TLU inputs from the veto's we can require a signal in the other scintillator.**



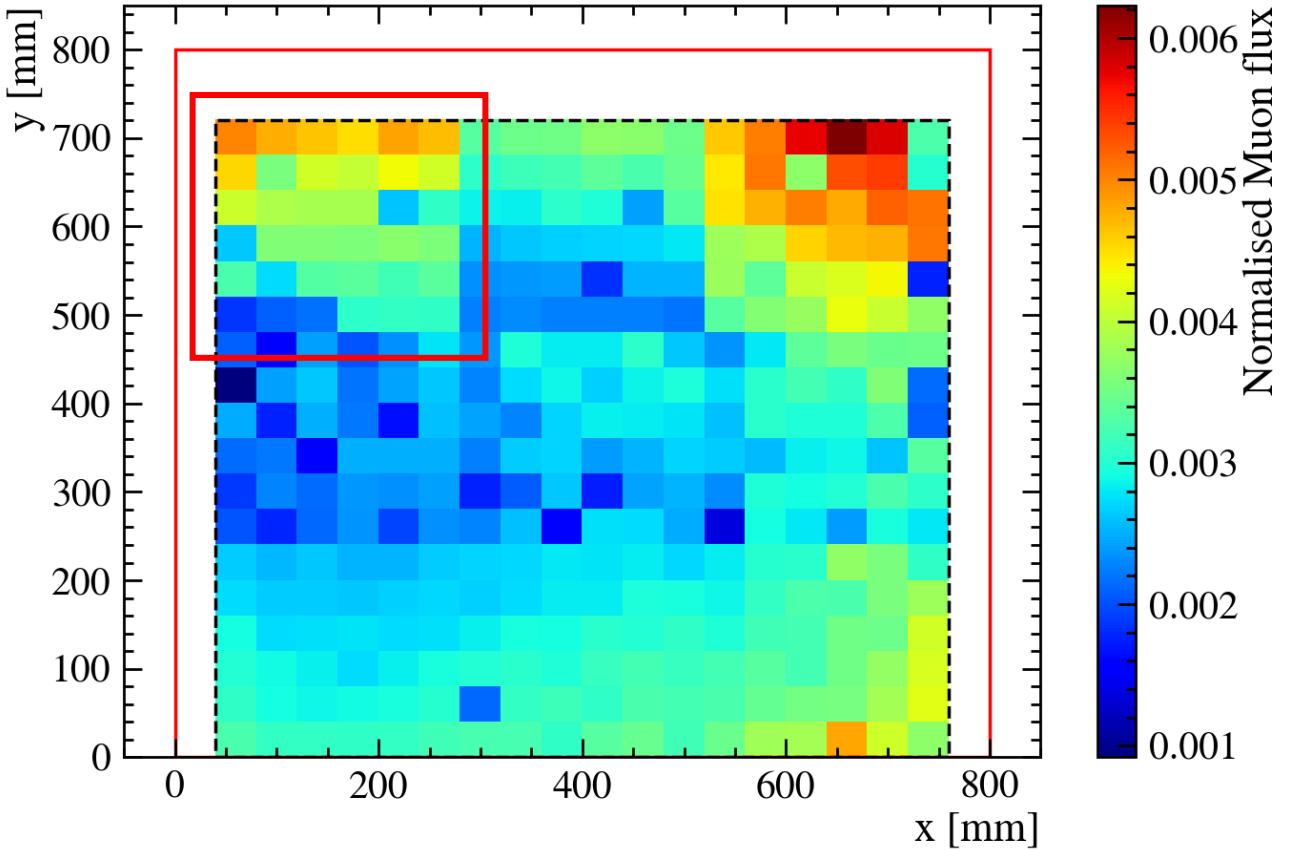


Muon Distribution (WIP)

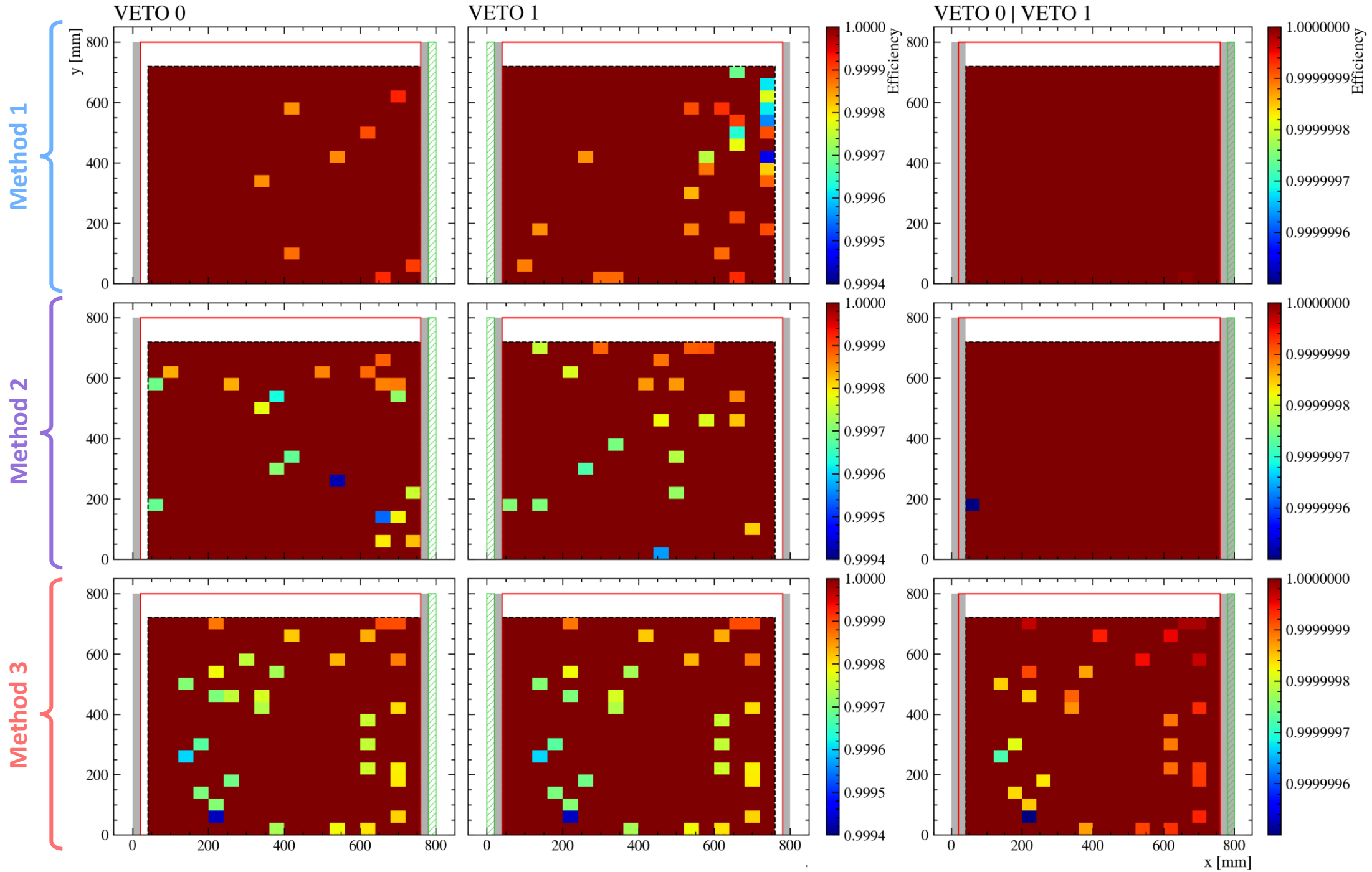
- The physics runs were used to look at the **muon flux across the AHCAL**.
  - Required a signal from either veto scintillator.
  - A clear structure can be seen due to the AHCAL.
  - 6 times more flux in hotspot than coldspot.
- **Plan to investigate this further!**
  - Plan to look at how the muon distribution changed with the β* and crossing angle at IP1.
  - Important to understand where the hotspots are for the location of the off axis detector.
  - Useful to validate the fluka simulation of the muon flux.
    - A better understanding of the contribution of the detector efficiency is needed for this.



Signal from either veto scintillator required



Method Comparison



Pros and Cons

Method 1

- A lot of statistics from many months of runs.
- Requiring the other veto scintillator verifies the tracks are muons.

- Can only include tracks that were stored given the other scintillator fired.
- Requiring the other veto scintillator is giving a fraction of inefficient events compared to the fraction seen in method 2 and 3.
  - The scintillators are independent and very efficient.
  - It needs to be further investigated.

Method 2

- Definitely independent of the other veto scintillator.
  - No prescale.
  - All events saved.
  - High threshold on other scintillator.
  - Only triggered on an event in the AHCAL.

- Few statistics.
- No information on the other scintillator.
  - Muon tracks only selected with the cuts.

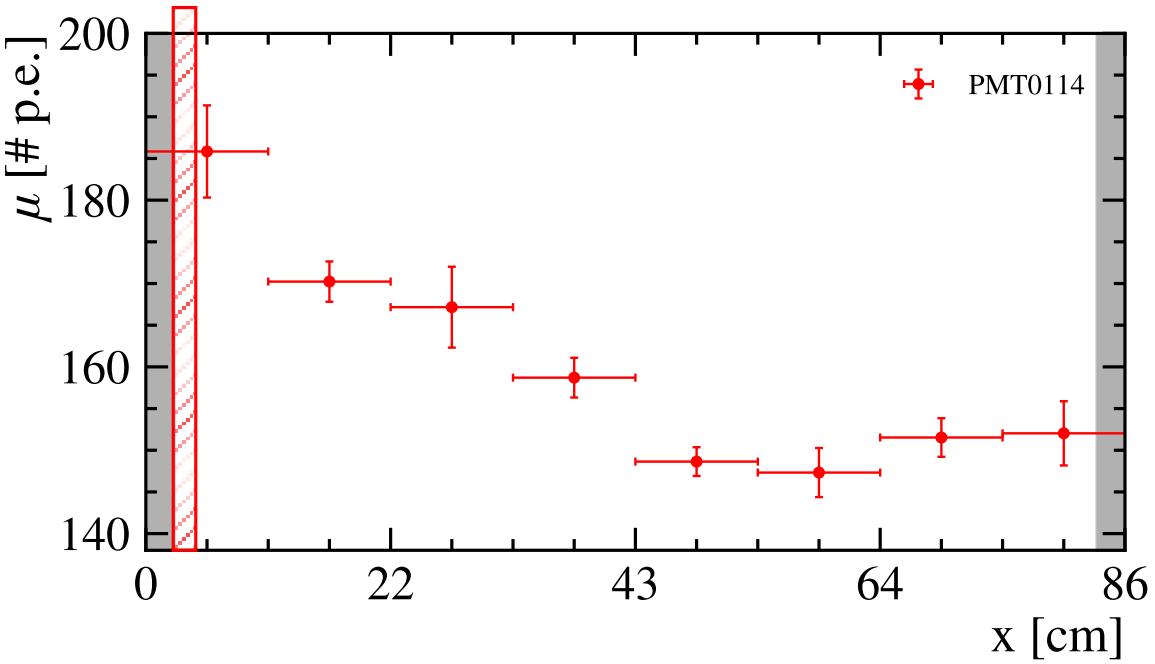
Method 3

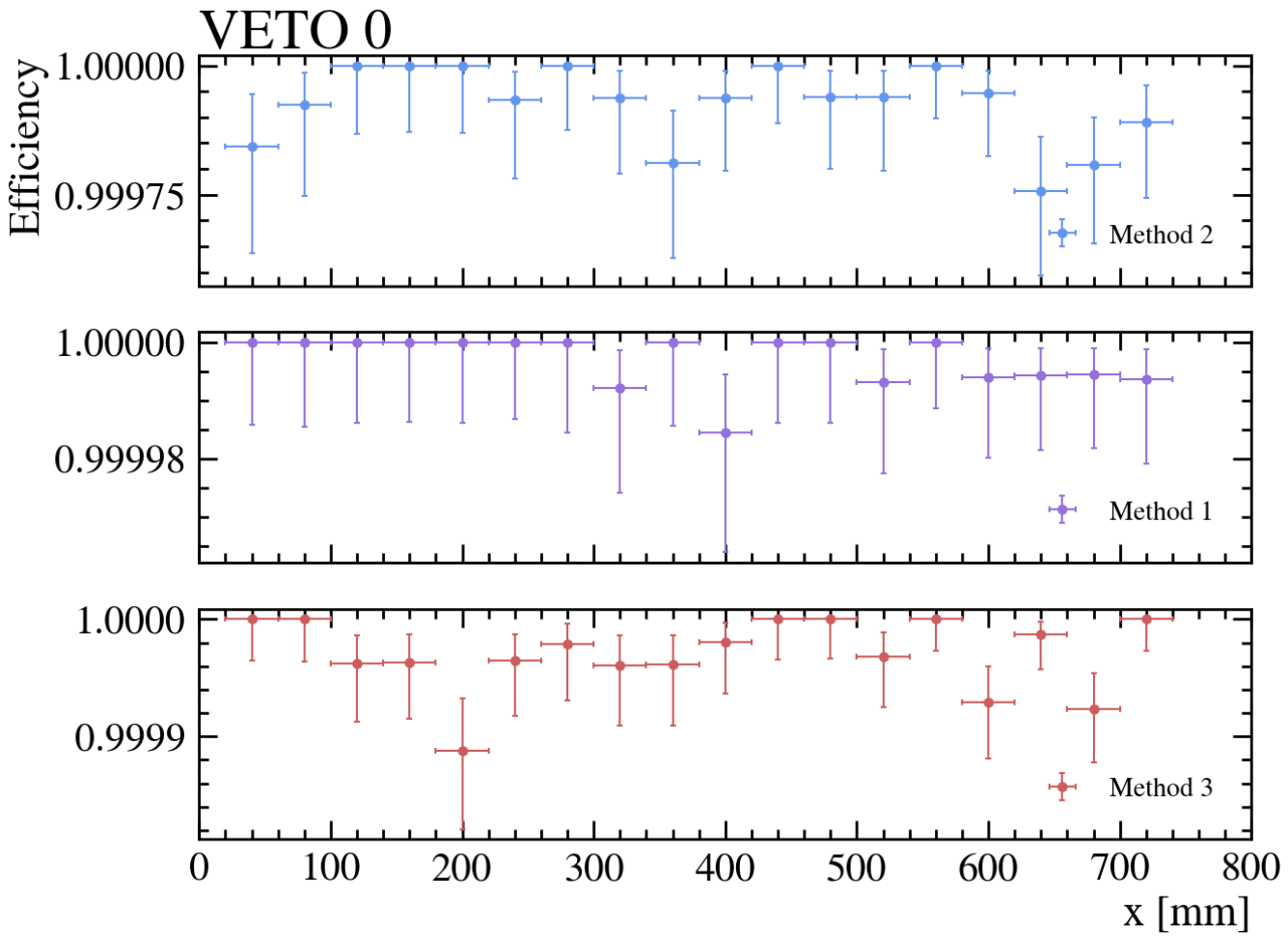
- Completely unbiased.
  - No prescale.
  - All events saved.
- Information from the other scintillator is stored.

- Not a lot of statistics.
- Looks highly correlated -> could be affected by crosstalk in the TLU.
  - Next the likelihood of cross talk from the other scintillator input or AHCAL inputs should be quantified.
- Vastly different number of inefficient events when requiring the other scintillator to fire.

UJ12 vs ENH1 (Very preliminary)

- From the study in ENH1, the light yield of the scintillator showed a clear dependency on the distance (in x) from the lightguide.
  - There is no significant decrease in efficiency due to the distance from the lightguide.
  - There is no apparent correlation in efficiency between methods over the position in the x direction.
    - If there is, it could not be seen with few statistics.



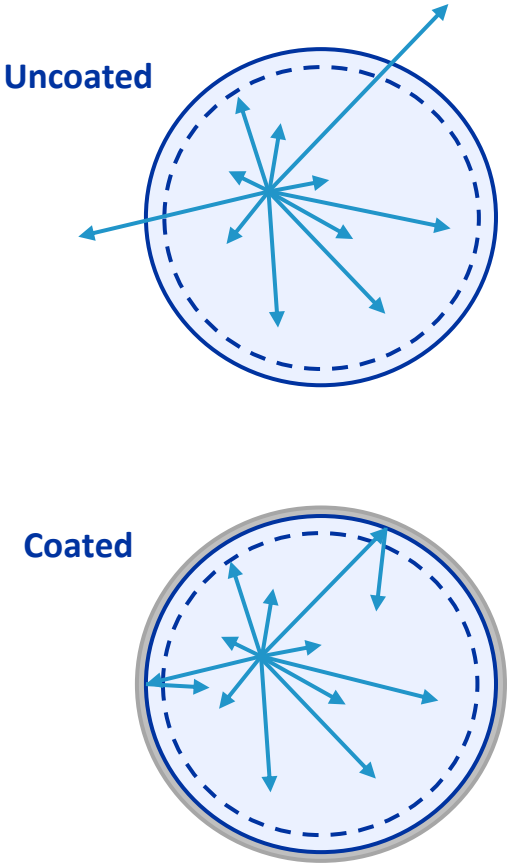


Conclusions and Next Steps

- **The veto scintillators are very efficient!**
- **3 methods used** but further work to validate each.
  - Each method agrees within statistical uncertainties.
    - However, the scintillators are very efficient, whether the efficiencies lie within a σ may not be the most indicative of a methods' validity.
  - Still to understand:
    - The smaller fraction of inefficient events for the physics runs vs runs without a prescale.
    - Whether TLU crosstalk is significant.
- **These methods can also be used to investigate the muon flux through the AHCAL.**
  - Useful to inform the placement of the proposed off-axis detector.
  - Further work needs to be done:
    - Clear detector effects seen.
    - The detector efficiency also needs to be considered.
    - How the flux changes with the β* and crossing angle.

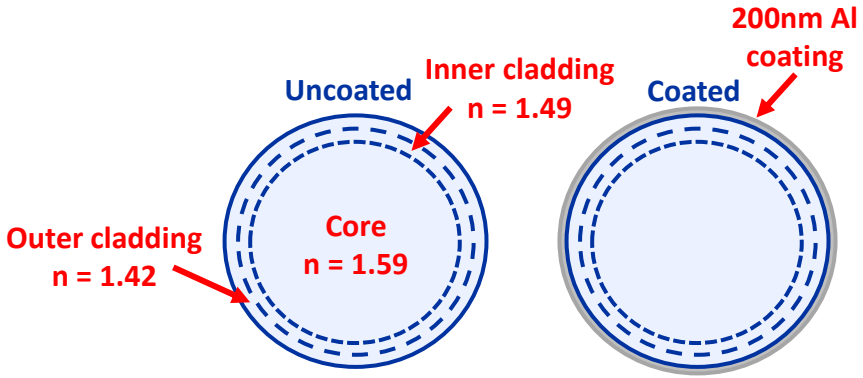
UV Coating for Thin Scintillating Fibres

- Reminder:
  - The core is a solvent (e.g. polystyrene) doped with a scintillator *O*(~ppm).
    - **The solvent is not transparent to the primary scintillated light (UV)**.
    - Doped with a wavelength shifter *O*(~ppm) to absorb the UV and re-emit in the visible.
- **In thin fibres, the mean free path of the primary scintillated light is *O*(diameter of the fibre).**
  - Unfortunately, some of the primary scintillated light could therefore escape the fibre before being wavelength shifted.
    - The **light yield of the fibre could increase** if more of the **primary scintillated light is trapped in the fibre.**
- **Aim: Can applying a thin, UV reflective coating improve the fraction of primary scintillated light that is wavelength shifted?**
  - As, in the past, this has been used to **reduced optical crosstalk** and (in theory) may also improve the light yield.

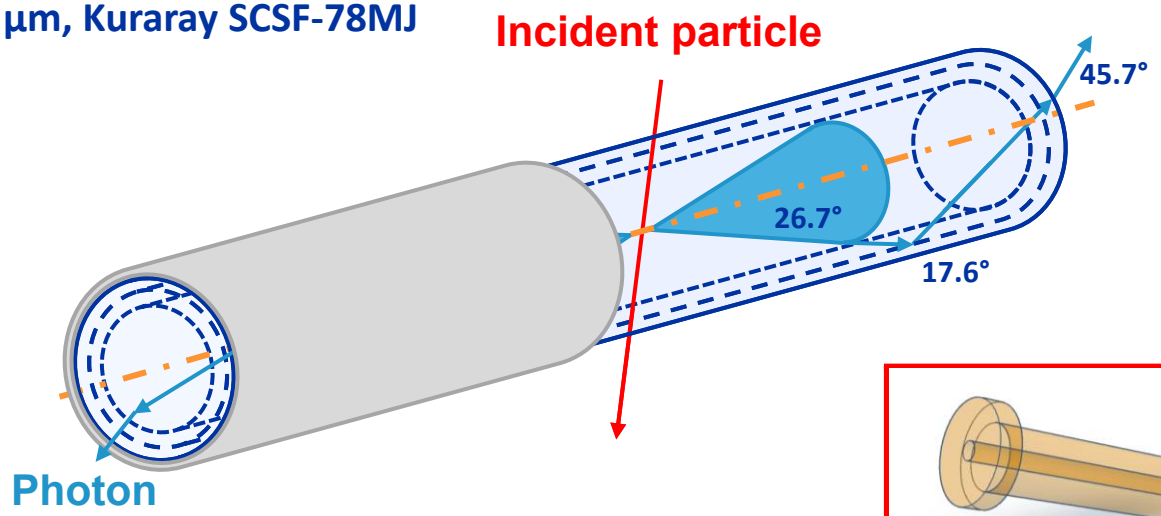


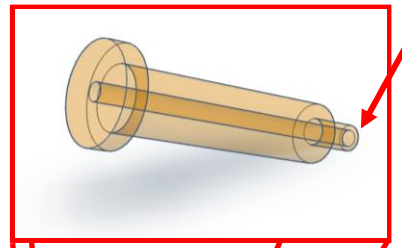
Coating Thin Scintillating Fibres

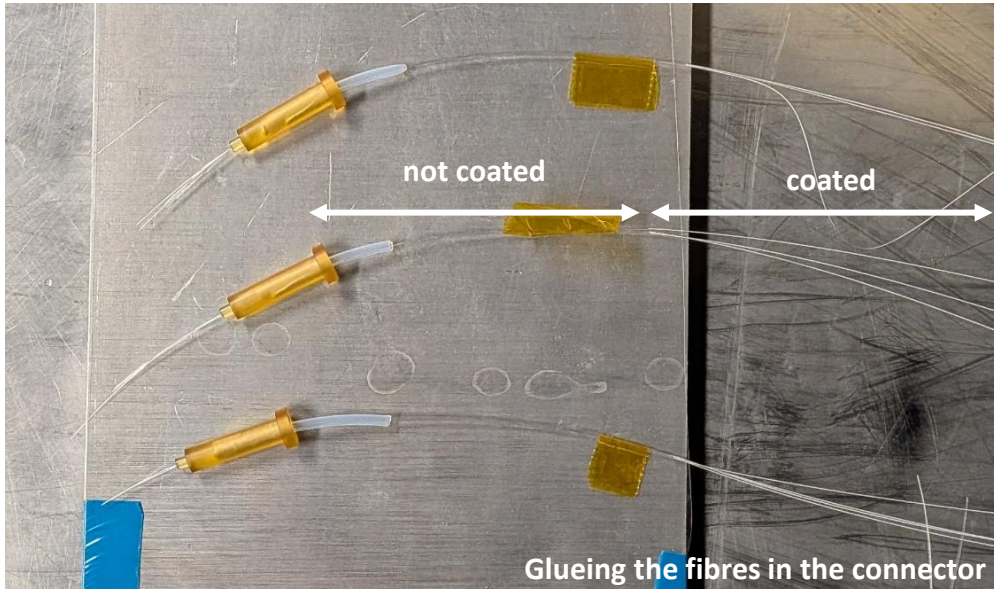
- For this campaign we used **round, double-cladded, Ø250 µm, Kuraray SCSF-78MJ** fibres, from the LHCb SciFi Tracker:
  - Primary UV scintillated light ~260nm.
  - WLS ~450nm.
- Half the length was coated with a 200 nm thick layer of aluminium by the **CERN EP-DT Thin Film and Glass workshop** (many thanks ☺).

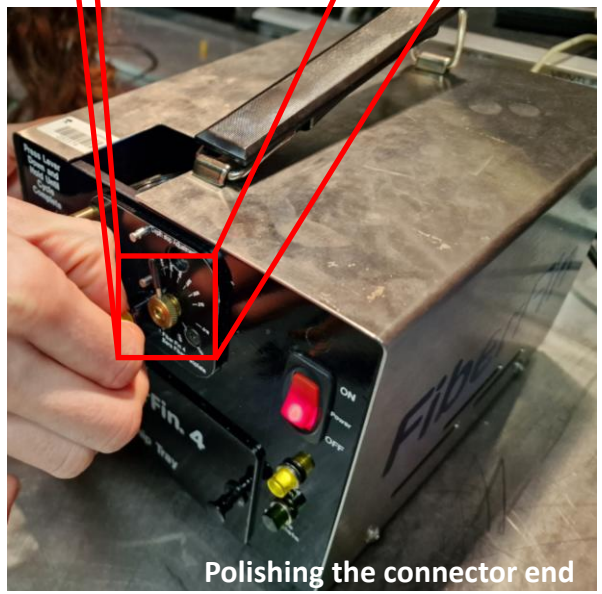


- The measured fibres were then glued with araldite to a fibre connector.
  - The end was machined to a flat polished surface using a diamond milling tool.



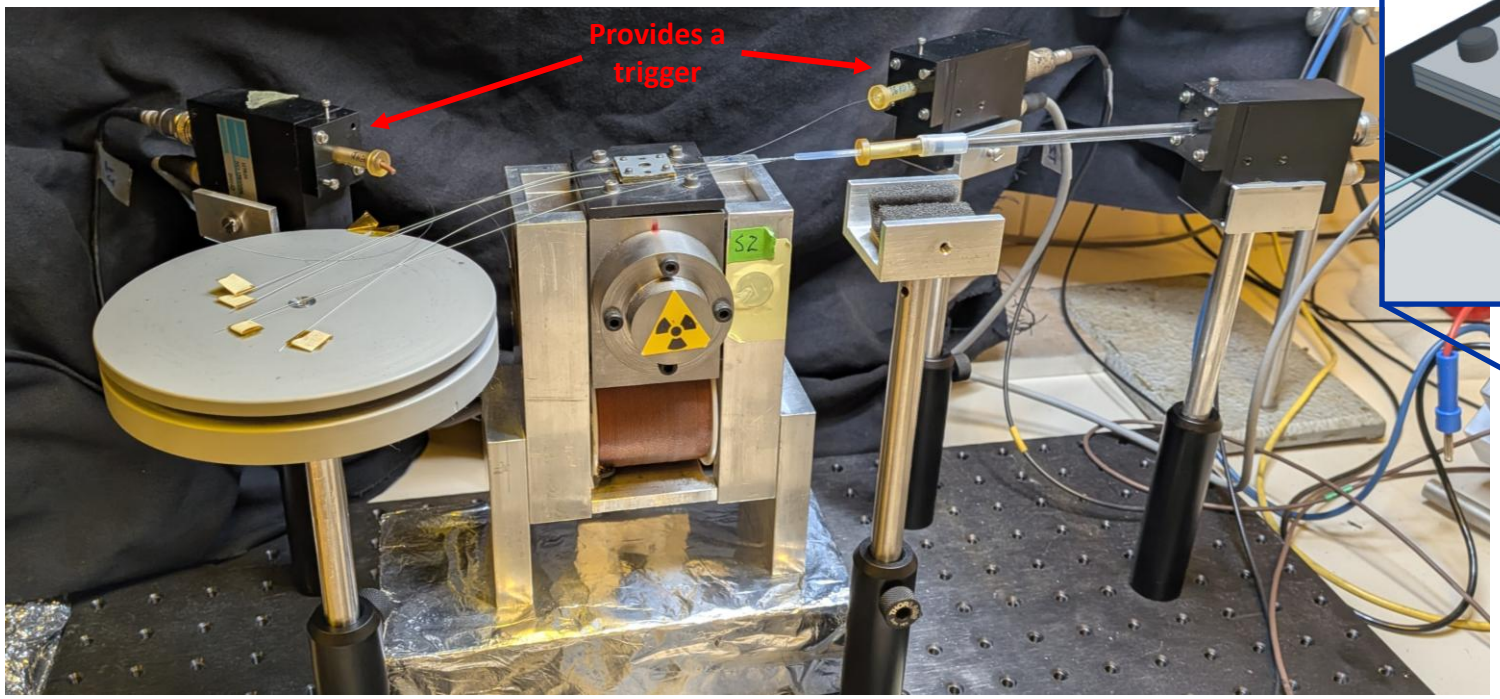


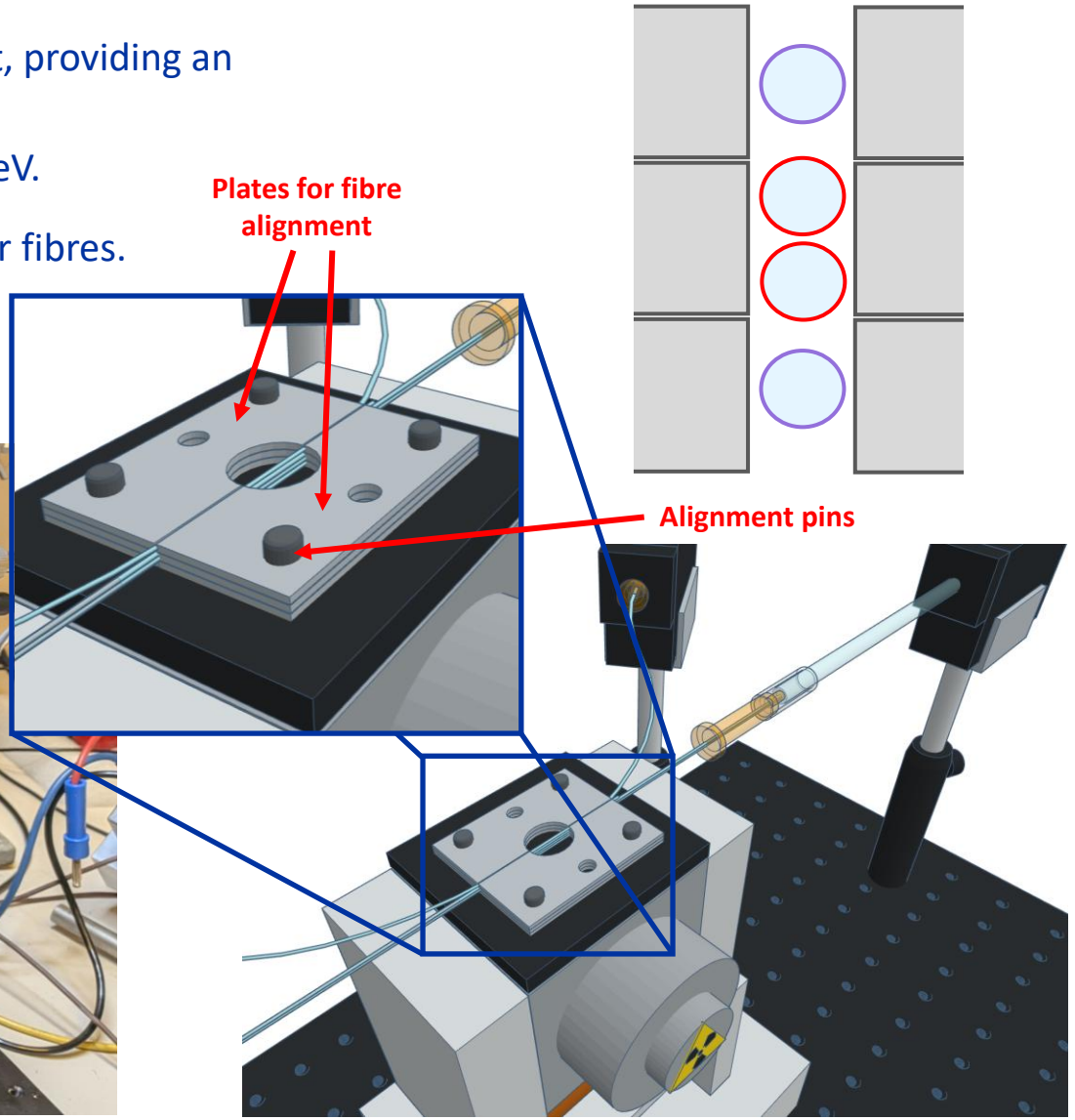




LY Setup – Trigger and Mechanics

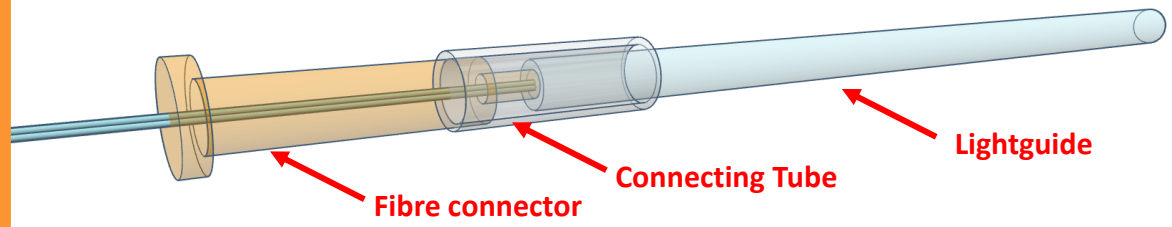
- A ^{90}Sr source is used with two tungsten collimators, and a monochromator allows us to select the electron momentum.
  - For the optimal trigger rate (~4.5Hz) 0.72 A is supplied to the magnet, providing an ~0.3 T field.
    - This selects minimum ionising electrons with $E_K \approx 1.1 \pm 0.1$ MeV.
- **Two fibres to be measured** are placed in the groove in between the trigger fibres.
- **Two trigger fibres** are connected to two PMTs with one fibre placed above and below the measured fibres.



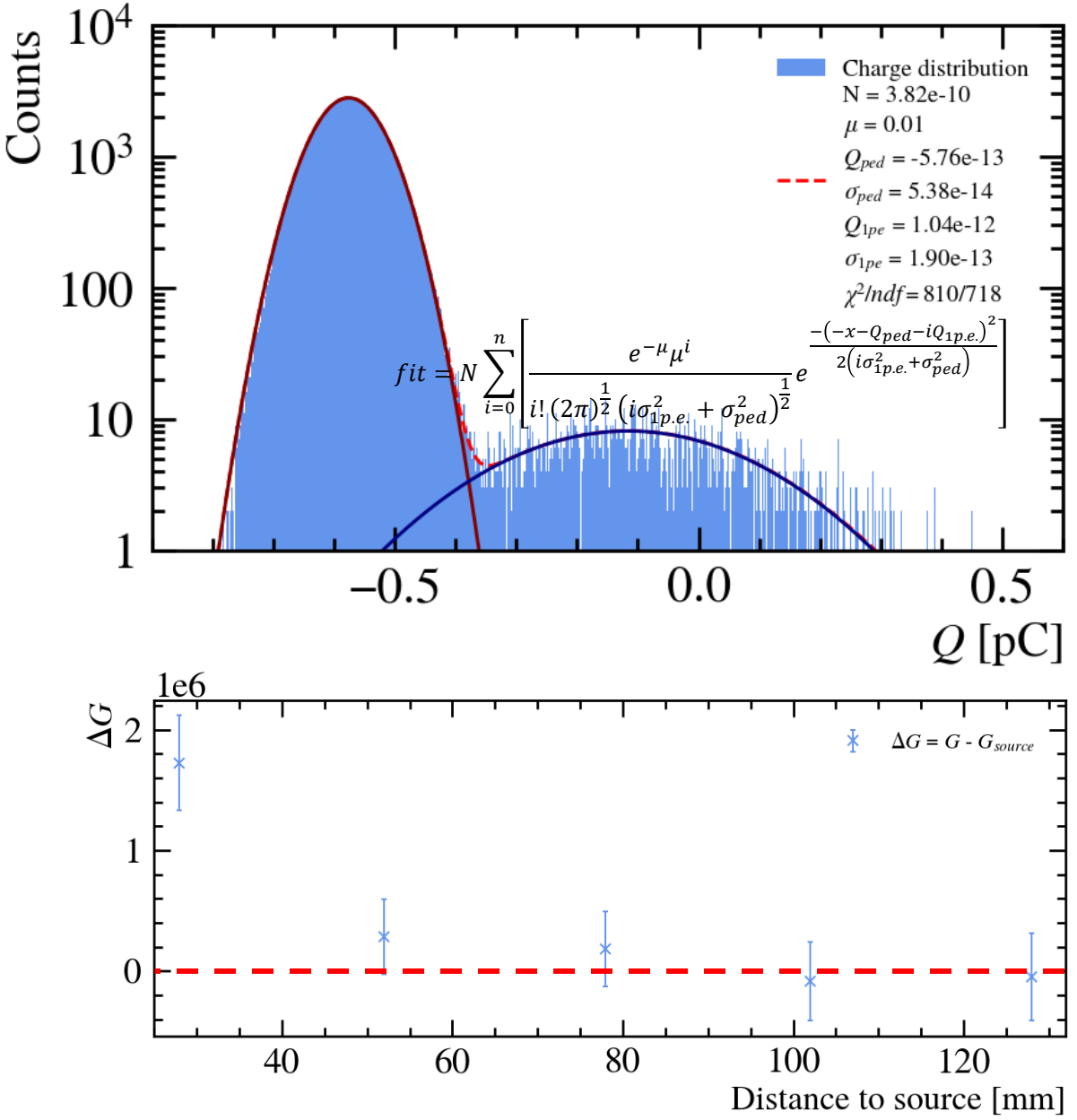


LY Setup - Debugging and Calibrating

- A third PMT to readout the fibres being measured.
  - **A LED was used for a 1 p.e. measurement for gain calibration**.
    - $G = (6.47 \pm 0.29) \times 10^6$
- To ensure the gain does not vary with position due to the influence of the magnetic field from the source's monochromator:
  - The LED was used to observe the effect on the gain to find the minimum distance from the source for the PMT.
- Therefore, a **minimum distance of 100mm from the source** should be kept to avoid any effect on the gain.
  - The distance between the PMT and source was increased by using a 120 x Ø5 mm lightguide.

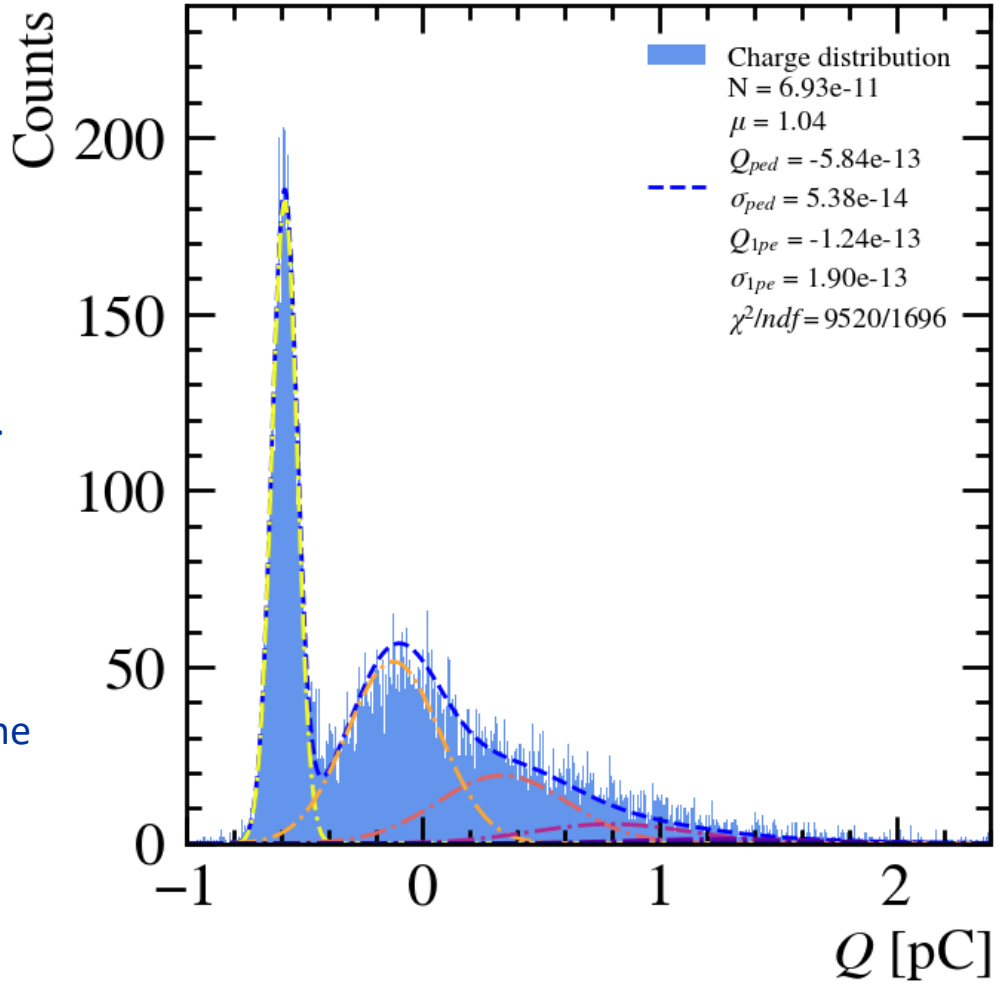


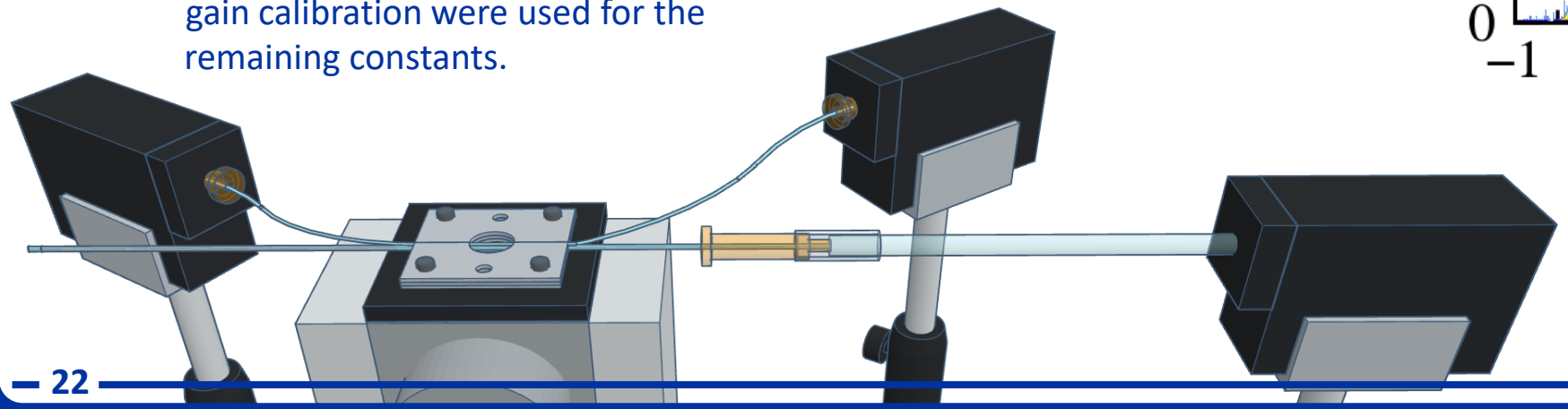
  - Hence a **minimum distance of 150 mm was used** (length of connector and lightguide)



LY Setup - Measurement

- **Two sets of fibres were measured**, with two fibres mounted on the source readout by the third PMT.
  - Better with more fibres but any more proved difficult to remove from the mechanics and increased the risk of breaking the fibres.
  - **The LY was measured over the length of the fibre**.
    - To reduce systematic uncertainties, we alternated measuring coated and uncoated positions.
    - During the scan, neither the lightguide nor the connector was moved.
      - As this is a relative measurement, this allowed us to avoid any statistical uncertainties that arise from the reproducibility of reconnecting the fibres/lightguide to the PMT.
- **For each position on the fibre, the charge spectrum was measured**.
  - The average number of p.e., the normalisation factor, and the position of the pedestal were kept as free parameters and the fitted parameters from the gain calibration were used for the remaining constants.





Results and Summary

- **The LY as a function of position is shown for both sets of fibres.**
  - A linear fit was applied on both the coated and uncoated data.
    - Set 1 had a μ = 1.05±0.02 p.e. for the uncoated half and μ = 0.95±0.02 p.e..
    - Set 2 had a μ = 1.10±0.03 p.e. for the uncoated half and μ = 1.11±0.02 p.e..
  - The work to understand the variations and uncertainties is still ongoing.
- **It was concluded that the aluminium coating does not have a significant positive effect on the LY inside the uncertainties.**

